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Conclusions and recommendations

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Energy for smart cities in an urbanised world

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Edited by Hans Larsen and Leif Sønderberg Petersen

Risø DTU
National Laboratory for Sustainable Energy

Risø Energy Report 10
Energy for smart cities in an urbanised world

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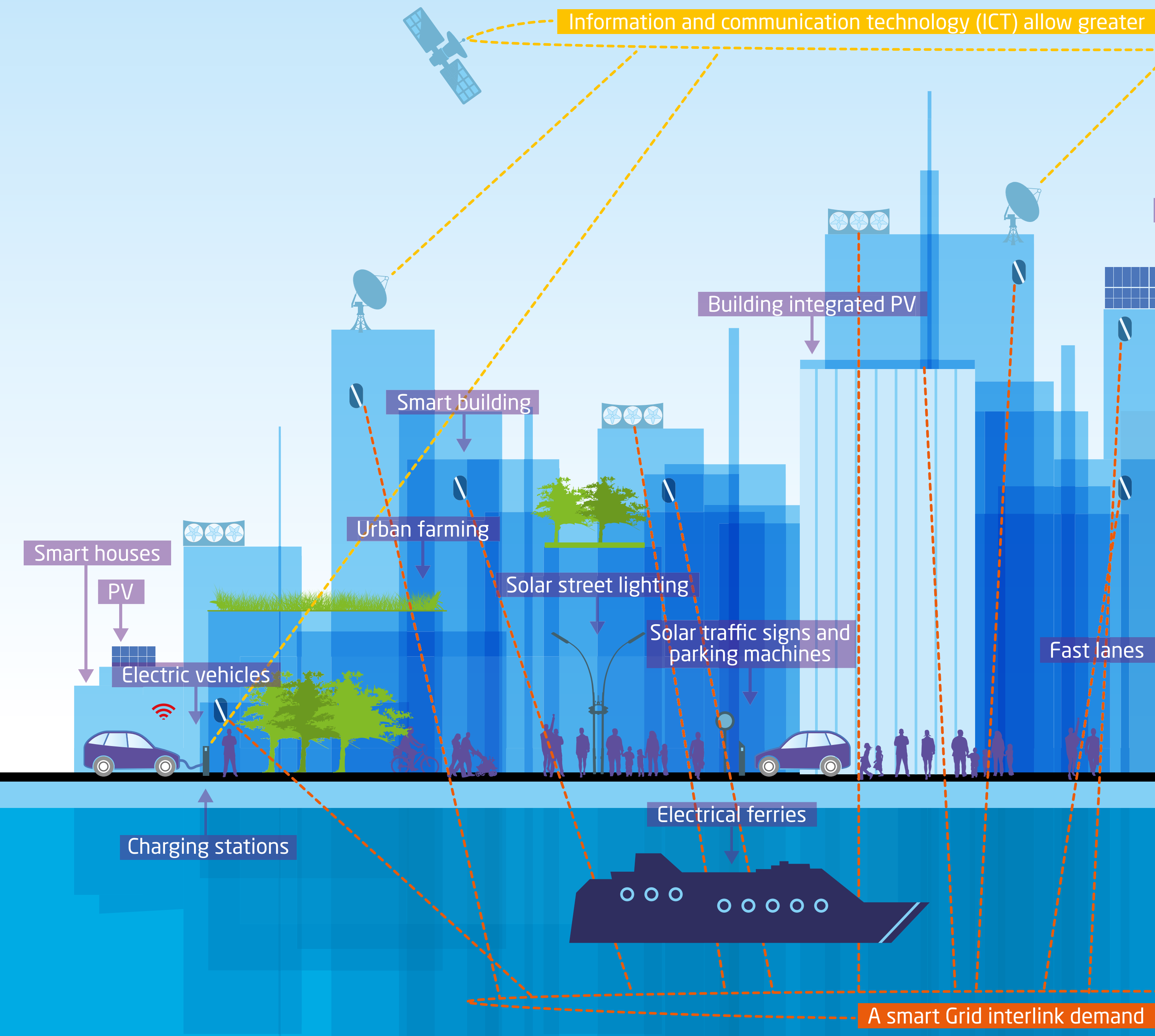
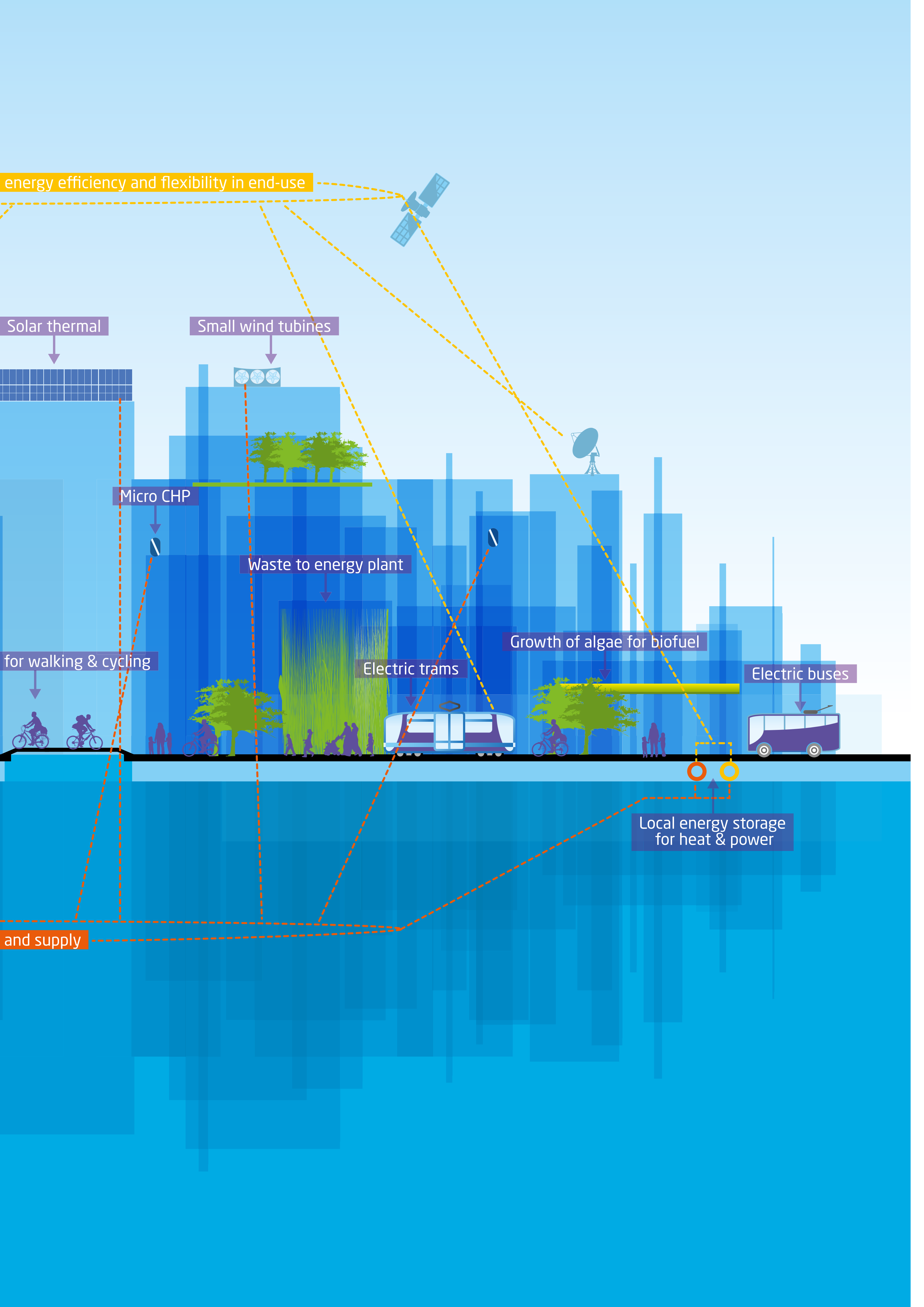
The creation
of a smart city
Turn page

The creation of a smart city



The concept smart cities is a new approach to what cities should do to become more liveable, economically successful, and environmentally responsible. The illustration shows how a city can be converted to an energy-efficient, consumer-focused and technology-driven smart city:

- Turn the buildings and houses to smart buildings and smart houses
- Organise distributed generation within the city limits
- Organise sustainable transport systems
- Build storage and conversion facilities
- Add the Smart Grid and exploit ICT


energy efficiency and flexibility in end-use
Solar thermal
Small wind tubines
Micro CHP
Waste to energy plant
for walking & cycling
Electric trams
Growth of algae for biofuel
Electric buses
Local energy storage for heat & power
and supply

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Preface

This Risø Energy Report is the tenth in a series which began in 2002. Volume 10 takes as its point of reference the rapid urbanisation of the world. UN population statistics show that global population is expected to surpass 9 billion by 2050, and nearly 6.3 billion people will be living in urban areas. Urban regions will thus absorb most of the world's population increase in the next four decades while drawing in some of the rural population as well: by 2050 there will be 600 million fewer people in rural areas.

A significant fraction of this growing urban population will be spread across a large number of small and medium-sized cities, but the projections also show that the number of megacities and other very large urban settlements will increase significantly. In 1975 the world's megacities (those with populations above 10 million) numbered only New York, Tokyo and Mexico City. Since then another 18 megacities have evolved and the number is expected to increase to 29 by 2025. Only five of these will be in OECD countries, showing that developing countries will dominate urban development.

The large cities and megacities created by this rapid urbanisation contribute to climate change, and in turn are affected by its consequences. For these and other reasons we need a new approach to what cities should do to become more liveable, economically successful, and environmentally responsible. Megacities of the future need to be smart cities: that is, energy-efficient, consumer-focused and technology-driven. This cannot be achieved simply by improving existing technologies. Instead we need a new smart approach based on smart solutions.

With this background the report addresses energy related issues for smart cities, including energy infrastructure, on-site energy production, transport, economy, sustainability, housing, living and governance, including incentives and barriers influencing smart energy for smart cities.

The Risø Energy Report series gives global, regional and national perspectives on current and future energy issues. Individual chapters are written by Risø DTU staff members and leading Danish and international experts. Each report is based on the latest internationally recognised scientific material, fully referenced, and refereed by an independent panel of international experts.

The target readership includes colleagues at Risø DTU, collaborating partners, customers, funding organisations, Danish government ministries and agencies, and international organisations such as the EU, the IEA and the UN.

Conclusions and recommendations

Hans Larsen and Leif Sønderberg Petersen, Risø DTU

By 2050 more than 6 billion people will live in urban areas, most of them in developing and less-developed countries. The number of megacities (with more than 10 million people) is expected to increase from three in 1975 to 29 by 2025. These cities contribute to climate change, and in turn are affected by its consequences. At the same time, urbanisation generally leads to increased demand for energy-consuming services such as housing and transport. This trend is further stimulated by increasing average income levels.

For these and other reasons we need a new approach to what cities should do to become more liveable, economically successful, and environmentally responsible: smart cities, that is, energy-efficient, consumer-focused and technology-driven.

This mindset will create opportunities in relation to the development of new efficient urban infrastructures, including cities optimised for economic activity, energy consumption and environmental impacts.

Urban density and the spatial organisation of cities are important parameters for energy consumption especially for transport but also for residential and commercial buildings. The dynamics of urban expansion show that density of cities generally decrease as income goes up. However, analysis shows that lower density is not only affecting energy for transport, but it tends also to pave the way for generally more sustainable cities.

In the context of energy a smart city is a sustainable city focused on low energy use, renewable energy and small carbon footprints. However, only new and emerging cities can become true smart cities. An example is Masdar City in Abu Dhabi, planned as a smart city since its foundation in 2008.

Existing cities, in contrast, will have to adopt compromises between their existing forms and the full potential of true smart cities. In Denmark for example, Copenhagen, founded in 1167, is aiming to become a sustainable and smart city with a strong focus on the energy sector, climate change, and the broader environment.

Energy in smart cities should be highly distributed and self-supplying to a large extent, so as to minimize the need for huge investments in high-capacity transmission lines from distant power plants.

A range of renewable energy technologies modified for installation in cities can meet these requirements. This includes small wind turbines, micro-CHP and heat pumps. Both solar thermal heating (and cooling) and photovoltaics (PV) are modular technologies that can be integrated in residential, public and commercial buildings. The production and use of urban biomass should also be promoted.

Energy networks in smart cities must themselves be smart, with integrated information and communication technologies (ICT) to enable greater energy efficiency and flexibility in energy use. Full integration of energy networks and the smooth running of an energy system supplied mostly from fluctuating renewable energy will require policies and technologies to manage demand response.

The buildings within a smart city are themselves smart, with internal systems featuring a high degree of interoperability thanks to ICT and connections to the smart grid.

People and goods in a smart city will be transported by vehicles running either on electricity produced from renewable energy or on fuel produced from biomass. Public transport should basically be driven by electric technology. Non-fuel-consuming transport such as walking and cycling should be encouraged.

A challenge will be to motivate consumers in smart cities to achieve sustainable development by using available technologies in smart ways. Motivation may be economic, but may also take the form of information, education, regulation, reorganization, or improved services. Smart technical solutions already exist; now they must be made available to consumers and backed up by suitable economic incentives.

Many energy- and ICT-technologies for smart cities are already available, but still needs further R&D to fulfill the needs of the future smart cities. This could be achieved through establishment of broad networks and collaboration between the business sector, research, local governments and other partners. Further, the market pull for these smart solutions will grow during the coming decades in order to reduce the global CO_2 emission, ensure security of supply and give access to modern energy for the poor people in the world's developing countries.

The Danish research system will in cooperation with the Danish energy- and IT industry be able to undertake the necessary basic research, development, demonstration, market maturation and commercialization.

The creation of a smart city
Inside front cover

Recommendations

1. The smart city concept offers a new, sustainable framework for a combination of policy and planning efforts combined with technological innovation with regard to energy supply and the way it is consumed in transport, housing, services and industry.

2. To exploit the full potentials of the smart city concept further research and development of technologies and systems for smart cities should be given high priority.

3. Smart technologies and systems should be tested and implemented individually or collectively on scales from new developments of single-family houses to entire part of towns in order to improve performance and bring down the costs.

4. New cities and new part of towns should be planned and buildt as smart cities, and the concept should be used as much as possible in future urban planning to address climate change and turn tomorrow's cities into good habitats with healthy economic growth.

5. By urban development of existing cities the smart city concepts should be implemented in order to utilize and test parts of the smart city concept wherever economical feasible.

6. Large scale test and demonstration projects in new cities as well as in existing cities will strengthen the basis for planning and developing future smart cities, both for large cities and mega cities.

7. The existing and emerging sustainable energy technologies need to be re-engineered for optimal performance in smart cities, a task that Danish energy- and IT industry together with the Danish research system should be encouraged to undertake based on their outstanding competences within these areas.

8. The same is true with regard to the development of smart buildings as active components in smart cities.

9. Smart transportation systems are a prerequisite for development of true smart cities, as economical growth is dependent of high mobility. Hence, individually and coherent transport demonstration projects are strongly needed.

10. The ongoing Danish research, development and demonstration of smart grids should be extended with projects aimed at smart cities.

11. R&D as well as information- and legislation initiatives should be initiated in order to motivate and make it attractive for the consumers to exploit the numerous opportunities in the smart city concept.

12. There is a need for new political framework conditions in order to increase research and development in technologies and systems for smart cities, in order to stimulate green growth in the industries involved and exploit the prosperous opportunities for export of knowledge as well as products.

The global energy scene in a world with growing urbanisation

John Christensen and Jorge Rogat, Risø DTU;
Jean Acquatella, Economic Commission for Latin America and the Caribbean

Urbanisation trends globally

The UN Global Report on Human Settlement 2011[1] estimates that close to four of the world's current seven billion people now live in urban areas. This figure is expected to increase to nearly five billion by 2030. In a similar way to general population growth, most of the urban increase will take place in developing and less developed countries. In Africa around 50% of the population is expected to live in urban areas in 2030, while in Asia Pacific around 52% will do the same. In comparison Latin American and the Caribbean (LAC) will have nearly 85% of the population living in urbanized areas by 2030 and this region is already the most urbanized in the developing world (see Table 1). This massive urbanization will have significant impacts on the environment, the way the national economies are structured and societies at large.

UN population statistics[2] has projected population development even further and the data shows the world population is expected to surpass 9 billion by 2050 of which nearly 6.3 billion will be living in urban areas. The urban regions thus will absorb most of the world's population increase in the next four decades while drawing on some of the rural population as well; there will be 600 million fewer inhabitants in rural areas by 2050. Increased population means increased demand for jobs and services like housing and transport, amongst others, and hence increased demand for energy.

A significant part of this growing urban population will be spread on a large number of small and medium sized cities, but the projections also show that the number of megacities and other very large urban settlements will increase significantly (see Figure 1). In 1975, the number of megacities (>10 million) only consisted of New York, Tokyo and Mexico City, since then another 18 megacities have evolved and the number is expected to increase to 29 by 2025[2]. Only five of these will be in OECD countries illustrating the fact that the dominant urban development will take place in developing countries.

Urbanisation challenges – focus on energy

Historically the rapid urbanisation started first in what are now OECD countries, but the Latin American and Caribbean (LAC) Region has almost the same level of urbanisation (approx. 80% in 2009) as North America, there is however clear signs of saturation urban expansion in LAC countries where growth rates have halved in the last decades. Africa and Asia currently only have around 40% of the population living in urban areas, but high current and expected rates of urbanisation for the next decades mean

Table 1
Urban population projections by region (2010 – 2030)

Region	Urban population (millions)			Proportion of total population living in urban areas (%)			Urban population rate of change (% change per year)	
	2010	2020	2030	2010	2020	2030	2010-2020	2020-2030
World total	3,846	4,176	4,900	50.5	54.4	59.0	1.81	1.60
Developed countries	930	988	1,037	75.2	77.9	80.9	0.61	0.48
North America	289	324	355	82.1	84.6	86.7	1.16	0.92
Europe	533	552	567	72.8	75.4	78.4	0.35	0.27
Other developed countries	108	111	114	70.5	73.3	76.8	0.33	0.20
Developing countries	2,556	3,188	3,863	45.1	49.8	55.0	2.21	1.92
Africa	413	569	761	40.0	44.6	49.9	3.21	2.91
Sub-Saharan Africa	321	457	627	37.2	42.2	47.9	3.51	3.17
Rest of Africa	92	113	135	54.0	57.6	62.2	2.06	1.79
Asia/Pacific	1,675	2,086	2,517	41.4	46.5	52.3	2.20	1.88
China	636	787	905	47.0	55.0	61.9	2.13	1.41
India	364	463	590	30.0	33.9	39.7	2.40	2.42
Rest of Asia/Pacific	674	836	1,021	45.5	49.6	54.7	2.14	2.00
Latin America and the Caribbean	469	533	585	79.6	82.6	84.9	1.29	0.94
Least developed countries	249	366	520	29.2	34.5	40.8	3.84	3.50
Other developing countries	2,307	2,822	3,344	47.9	52.8	58.1	2.01	1.70

dramatic changes will occur over the coming decades in these regions.

Like many other development issues growing urbanisation can be both a challenge and an opportunity, depending on how the challenge is managed. One risk that it is already evident is that more than one billion people in cities live in urban or peri-urban slums generally under very poor conditions and on a business as usual trajectory, the number of slum dwellers will increase by at least another billion by 2050.

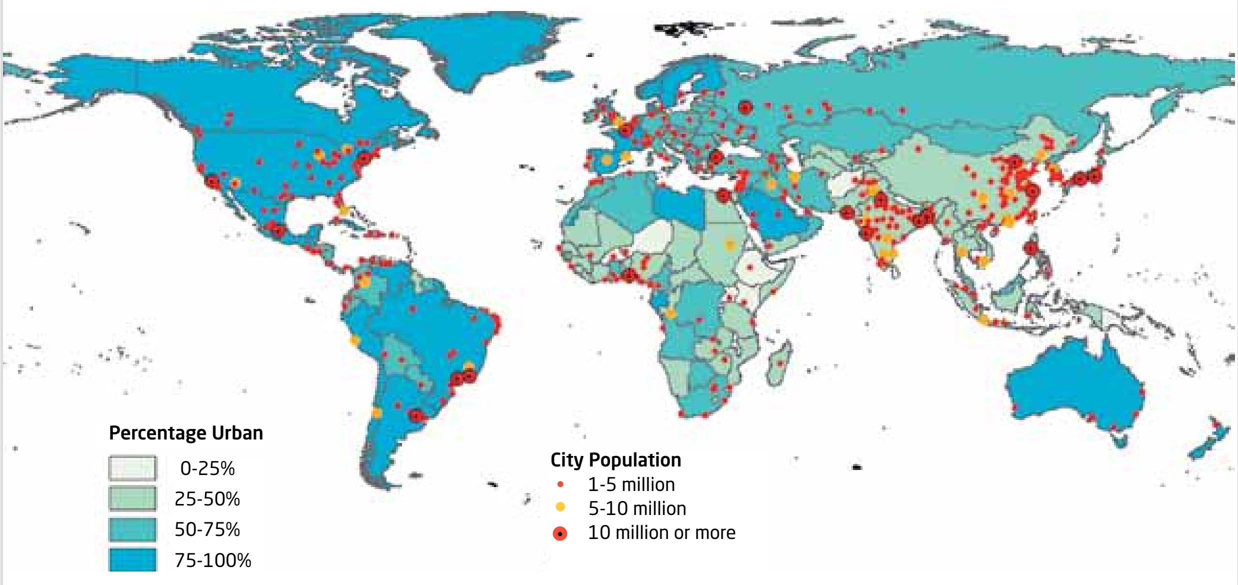
At the same time cities are generally key drivers of the national economy thus providing the majority of national output and consuming the bulk of energy resources. Even if there is no exact or commonly agreed definition for city boundaries, the IEA[3] and OECD[4] estimate that between 60 and 80 % of global energy use takes place in cities with a roughly similar share of global GHG emissions. In Figure 2, the IEA numbers for both global and city based primary energy consumption are presented providing a good indication of the importance of urban energy consumption and the gradual dominant consumption in non-OECD countries both for totals and for cities.

On the opportunity side is the fact that significant new urban infrastructure will need to be developed and put in place especially in developing regions while many OECD cities face an urgent need for renovation of urban infrastructure established in the early industrialisation period. The fact that the understanding of how to design urban settlements in more sustainable ways generally exists, provides the opportunity of expanding cities in more socially, economically and environmentally friendly ways. However, it does require dedicated planning and policies plus sufficient financing.

Urban density and the spatial organisation of cities are important parameters for energy consumption especially for transport but also for residential and commercial buildings. The dynamics of urban expansion has been analysed e.g. by Angel, et al[5] noting that density of cities generally decrease as income goes up. This is particularly reflected in the growth of sub-urban areas in OECD countries in the last decades, popularly termed "urban sprawl" associated with increased housing and shopping space. In 2000 the average density for cities in OECD countries was 2 to 3 times lower than that of developing countries, however along with the rapid urban population expansion in most

Figure 1

Urbanisation and localisation of large cities in 2025[2]



developing regions the density of cities is also declining basically confirming the trend towards urban sprawl as income increases, in spite of a significant share of poor dwellers not contributing.

The decreasing density of cities inevitably leads to increased travel both for work, leisure and shopping. Angel argues that the causal link between sprawl and transport can be complex i.e. that better transport options lead to new settlements like it has been happening around major infrastructure expansions like metros in Copenhagen, Athens and several other cities, but the dominant trend is that the expanding high income part of the populations desire more space and seek this in new expanding suburbs leading to increased transport needs. Figure 3 indicates this trend using data from Paris and even if the situation is more complex than just a reflection of sprawl, the illustration links between density and transport is quite clear.

Analysis by the World Bank[7] shows that density is not only affecting energy for transport, but it tends also to pave the way for generally more sustainable cities with lower service cost, higher energy efficiency in general etc. This is to some extent illustrated in Figure 4 linking urban density to GHG emissions per capita.

It is evident from Figure 4 that the relationship is valid for both developing and industrialised country cities, but it should be noted that GHG emissions also reflect the fuel use in local energy systems, which is contributing to explaining differences between e.g. Cape Town (mainly coal based electricity) and Rio de Janeiro (mainly hydro based). Compactness of cities are beyond the general income correlation affected by historical developments, geographical constraints, pricing policies for land and fuels (e.g. low US gasoline prices can be seen as an explaining factor for more urban sprawl in many major US cities compared to Europe).

Figure 2
World and City primary energy consumption from IEA 2008.

One specific example of different energy pathways for urban development is the case of China where there are some marked differences between clusters of cities with high per capita consumption and others following a distinctly lower energy pathway, this is illustrated in Figure 5.

As noted in Figure 5 the differences reflect a number of underlying conditions like climate, industrial activities etc. but it also reflects a stronger focus on planned city development, increased density and energy efficiency. The figure may therefore illustrate a more general development direction for Chinese cities over time, moving from low income high energy consumption patterns towards higher income and more energy efficiency.

While the discussion in this chapter focuses on how approaches to city development affect the energy service requirements, the subsequent chapters will explore in a lot more detail how these needs can be met in cleaner and more efficient ways. Focus throughout the report is on how to make cities and urban settlements more energy efficient and base their energy supply on cleaner energy sources for housing, transport, industries etc.

More sustainable urban development and energy consumption patterns

Cities play a key role in the national development of most countries and are therefore also well placed to contribute to their realisation of sustainable development. As discussed above urban centre growth leads to an increased demand for jobs and a number of services like schools, medical services and infrastructure. Two major approaches towards promoting more sustainable urban development are discussed in the following; firstly, adequate urban planning and secondly, a more sustainable energy use especially for the transport and building sectors, combined with an increased share of energy services provided by renewable energy sources.

Both the political and public awareness of the importance of cities for global and national energy consumption and associated GHG emissions has increased significantly in the last years and resulted in an emergence of a large number of enhanced actions by city councils and local governments on clean energy and climate change.

One recent example is the Mexico City Pact and Cities Climate registry launched at the UNFCCC COP 16 in Cancun late 2010 and ratified by more than 150 cities around the world ranging from smaller towns to a number of megacities. The Pact is organising voluntary action on reducing GHG emissions with a focus on energy efficiency and renewable energy, and many similar initiatives exist and are gradually translated into policies and actions with a strong focus on renewable energy provision and enhanced energy efficiency.

REN 21[8] has analysed local renewable policies and found that actions can be grouped in 5 categories:
- Target setting (GHG reduction, share of RE, biofuel use in municipal transport, etc.)
- Regulation (planning and zoning, building codes, economic incentives, purchase rules, etc.)
- Municipal action (green purchasing including energy, RE & EE in municipal buildings, utility engagements to green energy sources)
- Voluntary action and demonstrations (demo and pilot projects, financial support schemes, etc.)
- Information and awareness campaigns

The REN report has analysed actions in 210 large or mega cities around the world with a focus on OECD, Asia and LAC (Africa missing mainly due to lack of appropriate data) and found that most cities have some form of targets and very often information and awareness programs.

Regulatory and green procurement programs are common in EU and North America, but less so in other regions. All in all the REN analysis shows a large and increasing number of actions directed towards more sustainable energy service provisions in cities, but it does not provide any assessment of the achieved results, which can mainly be found at the level of individual examples. One example of structured urban development with a strong element of sustainability is the city of Curitiba in Brazil (see Box for details), but many examples exist of either integrated or partial action cities to improve sustainability. One recent and rather unique example is Masdar, a new urban development under construction for around 50.000 inhabitants in Abu Dhabi with the aim of having complete CO_2 neutrality, using a combination of urban and housing design, energy efficient appliances and strong focus on renewable energy sources. Another example of a city changing existing structures is Växjö in Sweden – a city of around 80.000 inhabitant - committed to becoming "fossil free" by 2015 through a strong focus on efficiency and renewable, especially biomass.

Many of the examples cannot be copied directly by other cities due to differences in structure, economy, environment etc. Nevertheless, they do provide inspiration and learning that can be shared and adapted to the local circumstances.

Figure 3
Density, car use and associated energy consumption for Paris[6]

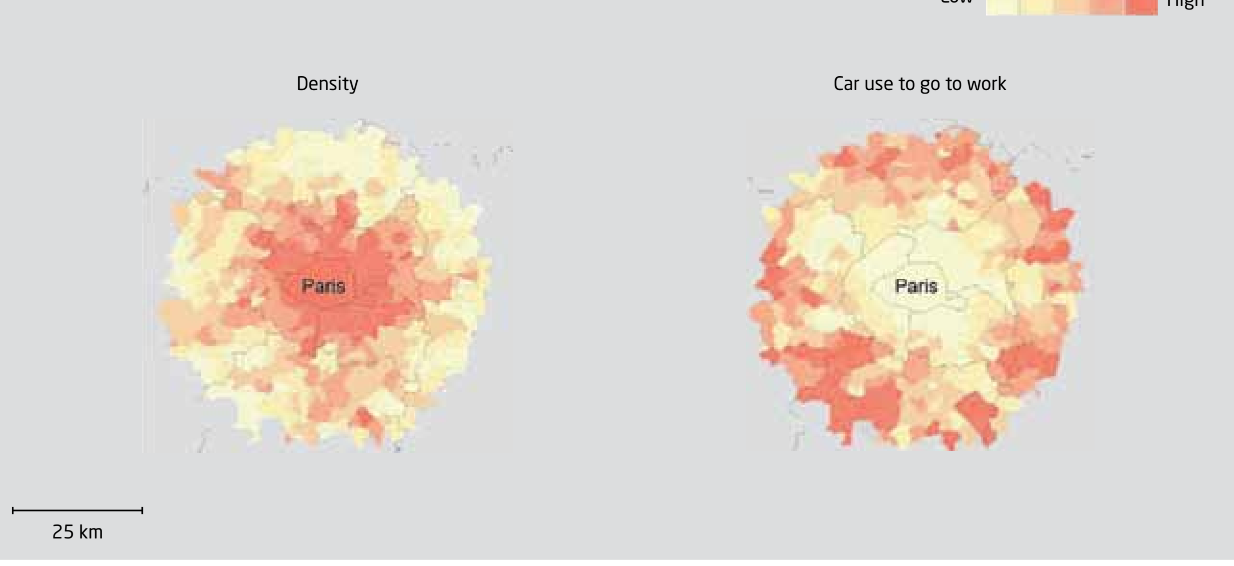
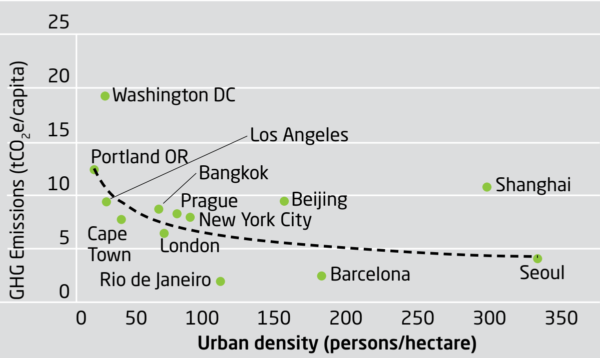


Figure 4
City densities and GHG emissions per capita[7].



Similar to specific energy and climate actions at city level there are a number of examples of how integrated urban planning focusing on efficient housing and transport systems have contributed to vast reductions of urban energy consumption.

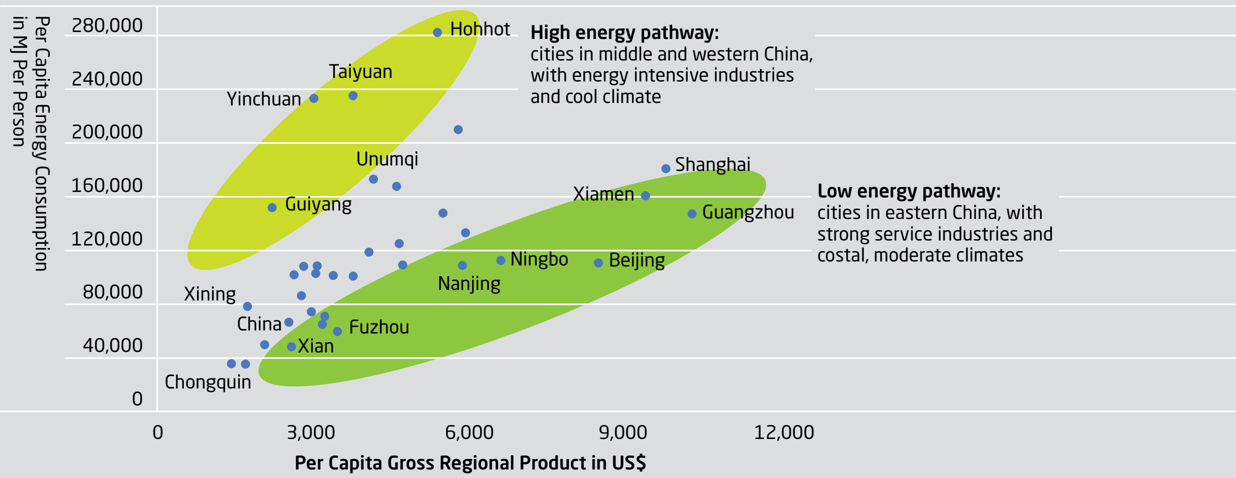
Generally two approaches for more sustainable urban development are being implemented focusing on i) compact concentric zones, and ii) integrated satellite cities[1]. The first approach deals with the earlier discussed issue of density and focuses on compact cities or the densification of these, where people are given the possibility of taking advantage of agglomeration economics while protecting the environment. The advantage of this model is that economic and social activities can be concentrated around the city centre thus significantly reducing mobility and thereby energy use for transportation. Integration of harbour or river front areas for new urban developments in cities like London and Copenhagen are examples of how intra city migration trends can be reversed although transport solutions in both cases could have been better integrated. A general lesson e.g. from the LAC region is that early and adequate transport planning in the design of dense urban development is absolutely crucial, as ex-post establishment of new infrastructure become either very costly or simply impossible[9].

The second model aims at achieving an integrated system of compact interactive satellite cities which are linked by strategically located transit lines or corridors where the population can be offered efficient and rapid transportation thus reducing energy consumption and hence both local and global emissions. In this context, the development of multimodal transportation systems, in which both motorised and non-motorised transport can be integrated is also crucial and will allow reducing car dependency. Cities like Curitiba in Brazil (see Box) and Medellin in Colombia constitutes good examples where sound urban planning has contributed to the development of more sustainable cities.

While there is no universal definition of the term “smart cities” the concept generally is seen to combine sustainability oriented urban planning efforts with the application of modern and efficient communication, transport and energy technologies. The term will be further discussed in the subsequent chapters.

Further references: 11,12.

Figure 5
Chinese city structures and per capita energy consumption.[7]



Curitiba[10]

While it is not easy to find good large scale examples of so-called smart cities, Curitiba has come a long way in terms of addressing some of the challenges with urban expansion. It is the 7th largest city in Brazil with a population of around 1.9 million and capital of the State of Paraná. The city is among the richest in Brazil with a total GDP of around 17 billion USD (Cinquina, 2008), which could indicate that its approach may not be replicable, but with the historical development the last three or four decades it is also clear that the strong focus on urban sustainability has been a contributing factor to the increased wealth.

The City has a long tradition of urban planning and has since the sixties focused on securing transport systems that allow both private vehicles and efficient public transport with road systems designed with dedicated lanes for Bus Rapid Transit systems. The ticketing system is designed for easy shift between transport systems and with as many as 2 million passengers per day it is possible to keep prices affordable also to many low income households.

Curitiba is also referred to as the ecological capital of Brazil, with a network of 28 parks and wooded areas with a strong focus on maintaining the original biodiversity of the area. Excess flood waters from the many rivers in the area are diverted into new lakes in parks to solve the problem of seasonal dangerous flooding.

In addition to the environmental concerns, the city management also addresses the social aspects and engages the population in the process through awareness programs and incentives e.g. related to waste collection and the city recycles around 70% of its waste at present.

The city has received worldwide praise for its urban planning and developments and aims to continue the further expansion in an orderly manner.

Conclusions and reflections

- More than half the world's population live in cities and this is expected to increase to around 60% by 2030. The OECD countries and the LAC region are already more than 70% urbanised so the major urban expansion will happen in Asia and Africa.
- Energy consumption in cities already constitute between 60 to 80% of the global total and a roughly similar share of global GHG emissions, so cities and the way they develop are crucial for future sustainable development of most countries.
- Urban planning offer opportunities to improve the performance and energy efficiency of transport systems. But the removal of existing distortions and for example regressive gasoline and other fuel subsidies need to be part of a comprehensive reform package, which can only change the situation gradually in the decades ahead.
- Many cities around the world are engaged in strong efforts to support local sustainability, and often go beyond what is happening at the national level. Many internationally coordinated efforts by cities and local communities focus on clean and efficient energy and climate change and the awareness is rapidly increasing providing a strong basis for further action.
- The smart city concept has become a framework for a combination of policy and planning efforts combined with technological innovation both in the way energy is produced in and for cities and the way it is consumed in transport, housing, services and industry. Some shining examples exist but generally the implementation of the concept is only emerging and the rest of this report provides examples of what can be done and how to do it providing an input to the policy communities that are responsible for implementation.
- Strengthening the capacities of national governments in technology policy, and of local governments in long-term planning of urban infrastructure investments, will be key to enable the deployment of more efficient transport and energy technology options in the decades ahead. International experience (Brazil ethanol etc.) suggests that long-term State planning and technology development/dissemination efforts are required to create alternative pathways for transport systems.

Planning the smart city

Poul Erik Morthorst, Risø DTU; Jessen Page, Ralf-Roman Schmidt, Austrian Institute of Technology (AIT), Austria

"The 100 years from 1950 to 2050 will be remembered for the greatest social, cultural, economic and environmental transformation in history – the urbanisation of humanity. With half of us now occupying urban space, the future of humanity is tied to the city." – Anna Tibaijuka, former UN Under-Secretary-General

Today the total population of the world is around 7 billion people, and this figure is growing by approximately 0.7% a year. By 2009 the number of people living in cities exceeded the number in rural areas. By 2050 world population is expected to reach 9.1 billion, of whom almost 70% will live in cities – implying that the urban population will grow by approximately 1.5% a year. This rapid urbanisation creates opportunities, but also a number of challenges to address in the decades to come.

Opportunities exist in developing new efficient urban infrastructures optimised in terms of economic activity, energy consumption and environmental impacts. However, only new and emerging cities can truly be made smart; redesigning existing cities will always involve compromises between existing solutions and new activities. In the following sections we look in more detail at the idea of the smart city and discuss a couple of examples.

What is a smart city?

The idea of the smart city crops up in several different contexts and so is not easy to define. Rather than focusing on single aspects, most of the literature uses the term to refer to a spread of capabilities ranging from smart infrastructure to overall sustainability[13,14]. In most cases real-time data provided through information and communication technologies (ICT) is considered essential to the life of the smart city.

According to reference[13] a smart city has six main characteristics:
- smart economy
- smart people
- smart governance
- smart mobility
- smart environment
- smart living.

Every smart city should perform well in each of these six dimensions, though their relative importance may differ from one city to another. Ways to shape consumer behaviour, including education, are also important. Above all, these characteristics should interact in ways that create synergies for the smart city as a whole taking into account that strong trade-offs between them do exist.

At present there are three main approaches to creating smart cities:
- establish an attractive and competitive working environment to create new business opportunities and knowledge centres;
- develop new urban infrastructures to improve economic efficiency, political decision-making and the lifestyles of the city's inhabitants;
- create sustainable cities with a focus on low energy use, renewable energy, small carbon footprints and environment-friendly handling of waste and water.

Since this report is about energy, we will concentrate here on the third approach: sustainable cities.

Low energy and sustainability

In June 2011 the European Commission launched an initiative known as Smart Cities and Communities. The programme recognises cities not only as the continent's main consumers of energy and sources of carbon emissions, but also as essential actors in the transformation of the European energy landscape. Cities have the greatest potential for energy efficiency; cities can cover a significant fraction of their own energy needs; and when planned and wired as integrated, inter-communicating "urban energy systems" that can adapt their energy demand to match fluctuating renewable production, cities can transform themselves from passive energy consumers to active players in a future European energy network.

The objective of Smart Cities and Communities is to allow the EU to meet its 2020 and 2050 targets for energy consumption and carbon reduction while sustaining or increasing the quality of life of its inhabitants. To meet this challenge, the Smart Cities and Communities participants have identified five key elements of a smart city:

Active buildings: Innovative concepts in the design of low-energy buildings, including their heating, ventilation and air conditioning (HVAC) systems, should be applied to both new build and the refurbishment of the existing building stock. By time-shifting their use of energy these buildings may act as active demand-side nodes in the urban energy system. They may also have their own energy production systems on site.

Energy supply technologies: Decentralised production of renewable energy (such as solar PV, biomass, heat pumps, geothermal, wind) and low-carbon energy (such as combined heat and power (CHP), waste industrial heat, and heat and electricity from waste), and the coupling of these energy sources.

Smart energy grids: Intelligent thermal and electrical grids, plus local energy storage, will enable the city to integrate its own decentralised energy production into the wider grid, and respond to fluctuating electricity production from a regional electricity network based on solar and wind energy. Smart energy grids also facilitate various demand-side measures.

Low-carbon mobility: Improved public transport systems, efficient multi-modal passenger and freight transport, and an increase in the proportion of vehicles running on alternative fuels.

Urban energy planning: The true characteristic of a smart city is the ability to treat energy demand, supply and distribution as a single system that can be optimised. This requires not only the implementation of the four components listed above but also an understanding of how they affect one other and how they fit the city as it exists or is planned.

Converting an ordinary city to a smart city is a complex process involving a large number of actions, technologies and stakeholders, so integrated planning is essential. Decision support tools are useful at the conceptual stage as well for detailed planning and operation.

Stakeholder involvement

For the ideas and technologies necessary to a smart city to be implemented successfully, they need to be understood and accepted by those who govern, design, finance, install and use them. These socio-economic aspects of the smart city are of paramount importance. The challenges are to get the right stakeholders involved in the right ways and at the right times, develop appropriate business models and financial arrangements, and set up new regulations and legal frameworks. The transition towards a smart city therefore requires an integrative approach at three levels: stakeholders, concepts and infrastructures/technologies, respectively.

An integrative stakeholder process is one that includes all the relevant stakeholders in the planning process for a smart city. These include the city administration, public transport, energy providers, building developers, local industries and SMEs, financial institutions, R&D experts and citizens.

To find the right strategy for a particular city, the stakeholders first have to develop an ambitious yet achievable "smart energy vision". This vision, which may be based on existing strategies, needs to be agreed by a majority of stakeholders and to lead to SMART (specific/measurable/achievable/realistic/time-bound) goals for the long-term future. The targets that result from the vision are:

- *qualitative*: ecological sustainability, integration of users, social and organisational innovations, and
- *quantitative*: a specific set of key performance indicators (KPIs) for variables such as CO_2 emissions, modal splits, energy efficiencies and production of renewable energy.

Once a vision has been agreed upon a strategy will need to be developed to meet the resulting targets for the long term (e.g. 2050) and the medium term (e.g. 2020). The exact targets and the ways in which they are integrated will result from discussions based around a set of scenarios based on both technical and non-technical measures. An example of technical measures is the installation of specific energy technologies, while a non-technical approach might be an information campaign on energy efficiency. The product of these discussions is a road map for the project.

Finally, an action plan is needed to show how appropriate policies, business models and financing schemes will move the project along its planned route. The process of developing an action plan helps to identify which technologies are needed and how they should be integrated and financed. It may show that new technologies are needed, in which case the plan will need to include the necessary R&D. A typical example is the information and communication technologies (ICT) required to transform a collection of energy producers, distributors and consumers into an integrated system.

Examples of smart cities

As every city is unique, so too will be its transition towards a smart city. Some cities will focus solely on integrating large-scale services such as energy, water, waste management and transport – this is typical of greenfield developments such as Masdar City in Abu Dhabi. Others will rely much more on the suggestions of small stakeholders – this is commoner in the transformation of existing cities such as Bottrop in Germany's Ruhrgebiet. The following sections look at both of these examples and also at Vienna in Austria, which has a nationally funded initiative to create smart cities.

Masdar City

Thought up by the government of Abu Dhabi, Masdar (Figure 6) is an initiative to create a smart city supplied entirely by renewable sources. Masdar is located in the United Arab Emirates, approximately 17 km south-east of the city of Abu Dhabi and close to the international airport. Construction began in 2006 and is expected to finish in 2025, by which time Masdar will have around 40,000 inhabitants.

Masdar is a new city, planned and built from the ground up. British architect Foster + Partners designed the city as an integrated whole that includes renewable energy supply, high-tech wastewater management, low-carbon transport and recyclable buildings. Its most important characteristics are:

Energy demand: Energy consumption is minimised through stringent building efficiency standards (including thick-walled buildings), low-energy lighting, smart metering and a smart energy control system that manages the power load on the grid. A special feature is the city's orientation from north-east to south-west, which lessens the effect of the hot daytime wind and takes advantage of cool night breezes.

Energy supply: Masdar promotes on-site renewable energy. The city already has one 10 MW photovoltaic (PV) plant fitted with 50% thin-film and 50% polycrystalline solar cells, and more are expected to follow. In the longer term, however, on-site sources will not be sufficient, so larger PV plants up to 130 MW are planned. Wind farms will also be established outside the city to provide approximately 20 MW.

Water management: The water consumption target of 180 l/person/day is to be achieved mainly through efficient plumbing and appliances, but also with the use of smart meters to detect leaks. Wastewater is treated and recycled for use in gardens and parks.

Transport: Much is being done to keep traffic out of the city. Sidewalks and paths make walking a convenient way to reach many destinations. A public transport system consisting of light rail, metro and electric buses will provide most of the powered transport. A demonstration project uses electric-powered, single-cabin vehicles for rapid movement of both people and freight.

Recycling of building materials: Extensive evaluation of building materials has reduced both the environmental and economic impacts of construction. The timber used is close to 100% sustainable, and aluminium used for facades is 90% recycled. "Green" concrete in which some of the cement is replaced by ground blast-furnace slag reduces carbon footprint by 30–40% compared to ordinary concrete.

InnovationCity Bottrop

Bottrop is a city of approximately 120,000 people in the Ruhr industrial area of North Rhine-Westphalia, in the western part of Germany. Historically, the development of the city was based on coal mining and railways. Nowadays Bottrop is home to factories for coal-tar derivatives and other chemicals, textiles and machinery.

Figure 6

Masdar is a new city planned and built from the ground up. It is designed to be integrated and sustainable, with renewable energy supplies, high-tech wastewater management, a low-carbon transport system and a recyclable building environment. Pictures: www.masdar.ae

In spring 2010 the development organisation Initiativkreis Ruhr, in cooperation with 67 companies, launched a competition known as InnovationCity Ruhr. The aim was to choose a city that could be transformed into a low-carbon sustainable city, including energy-efficient redevelopment of existing buildings and infrastructure. In Europe, which generally lacks the space to build brand-new cities, the redesign of existing cities is crucial in the transition to sustainability.

From the 16 participating cities, Bottrop was chosen as the winner. Important in this success were Bottrop's comprehensive action plan, which includes a large number of stakeholders, and also the overwhelming support from citizens, more than 20,000 of whom signed the proposal.

The ambitious plan is over the next ten years to transform approximately half of Bottrop into a low-energy area whose energy consumption and CO_2 emissions will be half those of today (Figure 7). The next two to three years will see pilot projects in six areas: residential, non-residential, mobility, energy, urban development and "activation" (see below). The technologies involved include low-energy appliances, efficient heating systems based mostly on renewable energy, and hydrogen/electric vehicles. Once the results of the pilot projects are in, a master plan for the chosen part of Bottrop will be prepared.

An important part of the project is the inclusion and commitment ("activation") of stakeholders. InnovationCity Bottrop is supported by more than 30 companies including BASF, E.ON, IBM and Siemens. More than ten universities and research institutions are involved, and there is close collaboration with local and regional public institutions and ministries.

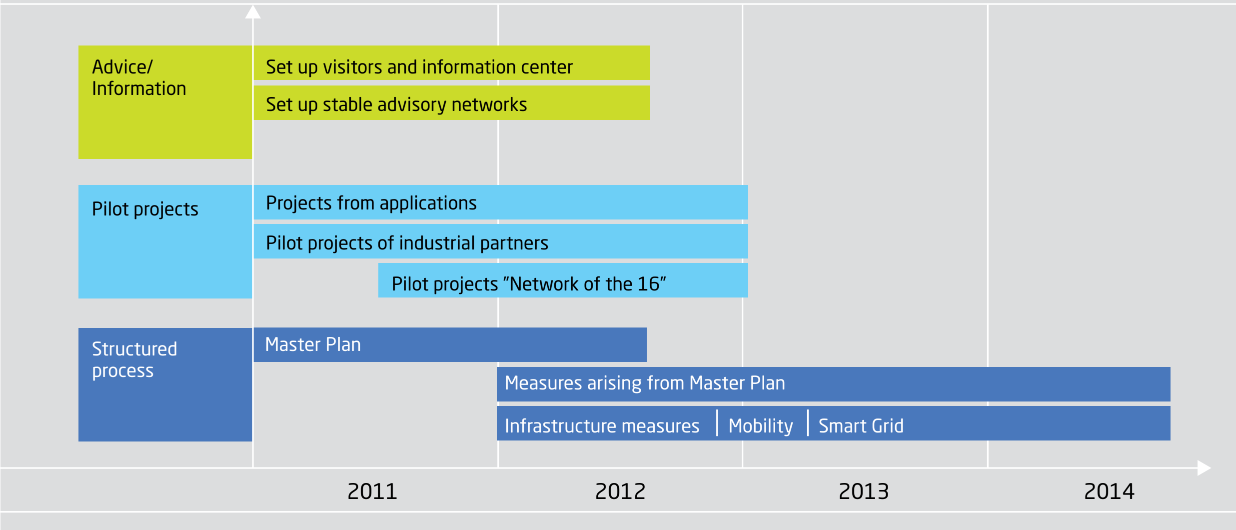
Smart City Vienna

Vienna was one of the first of the 20 Austrian cities funded under a national programme[14] to plan their transformation towards energy efficiency. Smart City Vienna[14] will meet the European Commission's 2020 and 2050 targets for energy efficiency, renewable energy production and carbon reduction. On the project team are representatives of the city administration (urban planning and energy planning departments), the local energy and transport utilities, building developers, energy hardware suppliers, research institutes and consultants.

Potential stakeholders attended a series of two-day workshops to create a "Smart Energy Vision 2050", a "Roadmap for 2020 and Beyond" and an "Action Plan for 2012–15". The city-wide energy master plan resulting from this consultation will feed into Vienna's future strategic documents such as the upcoming Urban Development Plan and Climate Change Action Plan. It will also help to identify demonstration projects consistent with the city's short-, medium- and long-term plans to become a smart city.

Figure 7

Bottrop, winner of the InnovationCity Ruhr competition, has a comprehensive action plan with a large number of stakeholders and overwhelming support from its citizens.



Smart city initiatives in Denmark and Europe

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Cities around the world are developing programmes for sustainable development and urban energy systems with the aim of meeting policy objectives relating to economics, energy security, climate change mitigation and urban development. This chapter provides an overview of European and Danish smart city initiatives within the context of the EU Strategic Energy Technology Plan (SETP)[16].

The smart city plans discussed here are built on a broad set of existing initiatives. In the case of Denmark, for example, a typical starting point is a climate-related policy to achieve carbon neutrality or zero emissions. Other cities focus more on specific energy system issues, for example the large-scale integration of fluctuating renewable energy. Yet others are inspired by a broader set of planning objectives, including the cultural and social aspects of city life. It is important to recognise that the world does not yet have any smart cities as such. At the moment, the smart city is a concept inspired by planners' visions and small demonstration projects.

In this way we can say that the principles of the smart city are embedded in ongoing planning initiatives and models. The technologies and designs finally chosen will depend very much on what is already going on in any particular city, and the examples we give here demonstrate this variety. Such flexibility implies that the planning and creation of smart cities involves many people from many different backgrounds. Stakeholders include politicians, technical experts, citizens, businesses, energy suppliers, transport, water and waste management.

Smart cities in Europe

Though as yet there are no smart cities in Europe, there is no shortage of plans to make cities more environment-friendly and whatever else is the term "smart" is understood to include. One of the main drivers for these ongoing initiatives is the low-carbon and renewable energy strategy within the European Strategic Energy Technology Plan (SETP)[16].

The SETP concludes that accelerating the large-scale deployment of low-carbon technologies will require a systems approach and organisational innovation encompassing energy efficiency, low-carbon technologies, and smart management of energy supply and demand. The SETP includes technology roadmaps to serve as a basis for strategic planning and decision-making. It suggests a collective approach to research, development and demonstration projects, and implementation with a clear focus on integrated programmes, as in the European Industrial Initiatives. The latter include a smart city initiative highlighting the importance of energy efficiency, integration of renewables and intelligent energy management systems in cities. Another specific SETP goal is to see sufficient market take-up of energy-efficient and low-carbon technologies, and to effectively spread best-practice examples of sustainable energy at city level across Europe.

In parallel with the Industrial Initiatives, as part of the SETP the European Energy Research Alliance (EERA) is asking key European applied research organisations to align their R&D activities to the needs of SETP priorities. As a result, the Austrian Institute of Technology (AIT) is taking the lead in a joint programme of applied research on smart cities. AIT is also creating links to universities carrying out fundamental research relevant to smart cities. In Denmark, the Technical University of Denmark is co-ordinating EERA network activities through the DTU Climate Centre at Risø DTU.

The CONCERTO initiative

The first cross-cutting research and implementation network created by EERA is the CONCERTO initiative[17], which is also the first of its kind to support a holistic approach to energy in the building sector. Instead of focusing on single measures or technologies, CONCERTO takes in a combination of measures including energy demand, supply and distribution, and socio-economic factors. Currently involving 58 communities in 22 projects across 23 European countries, the initiative offers a unique wealth of solutions that have been tested in the real world. CONCERTO is therefore a good basis from which to take the next strategic steps towards the smart cities of the future and a zero-emission society.

The accompanying CONCERTO Plus and CONCERTO Premium projects add value by developing an information base to support the decision-making processes of the European Commission and the creation of appropriate regulatory frameworks. CONCERTO helps to ensure effectiveness and repeatability by:

- setting benchmarks for energy efficiency in buildings;
- creating real case studies for the use of renewable energy in buildings; and
- demonstrating zero-energy buildings.

The Commission is now preparing a Smart Cities and Communities initiative that builds on the organisational framework of the SET Plan and other European initiatives for energy-efficient cities such as the Covenant of Mayors, CONCERTO, CIVITAS and the Green Digital Charter. The results of all these programmes are helping to make smart cities a reality, starting with single buildings and moving step by step towards a holistic approach taking in whole districts.

The experience of the CONCERTO participants is the basis of a new approach to urban planning and urban energy management based on the views of all stakeholders. The result is a body of best-practice guidance on topics such as how to design and build low-energy buildings and retrofit existing buildings to current standards.

Energy monitoring has so far been used on individual projects only at small scales. Multi-project technical databases such as those created through CONCERTO, however, can collect and analyse enough information to produce results that are useful for large-scale energy management.

In a similar way, renewable energy systems in current community planning are mostly single systems, with no holistic approach. Successfully integrating renewable energy into city-wide planning processes requires technologies to be assessed in relation to broader markets, policies and financial conditions. Further research is needed on how to scale up existing tailor-made finance packages for small innovations, with the aim of developing large-scale life-cycle finance schemes featuring new market players and financial products.

The development of smart cities requires the participation of high-level policymakers such as mayors and city councils, but at the moment senior politicians are not always involved in planning decisions at community level. Another important area of research in smart cities is therefore how to create a political climate that puts the development of smart cities at the top of policymakers' agendas and secures their commitment.

Lessons learned in CONCERTO should also feed back to the European Energy Performance of Buildings Directive (EPBD) and similar legislation.

Amsterdam Smart City

Amsterdam has already put in place large parts of the smart city vision. Amsterdam Smart City is an initiative of the Amsterdam Innovation Motor (AIM) and the grid operator Liander, in collaboration with the city government. The project is supported by the European Commission's European Regional Development Fund. The Dutch research organisation TNO provides an independent guarantee of research quality across the various sub-projects.

The idea of Amsterdam Smart City is to bring together public and private partners to test new initiatives through small-scale local pilot projects. Once the pilot projects have helped to show which initiatives are feasible, the best ideas can then be implemented on a large scale[18].

Projects under the four headings Working, Living, Mobility and Public Space were begun during 2009–2011. The first three of these areas are each responsible for roughly one-third of the city's total CO_2 emissions[19].

Amsterdam's "Climate Street" on Utrechtsestraat is a city centre street where around 140 shops, bars and restaurants are showing off a range of renewable technologies. Here and elsewhere in the city, energy-saving and low-carbon demonstrations include:

- electric vehicles to deliver goods and collect waste;
- solar-powered lighting for tram stops and billboards;
- integral compactors on bins allow five times longer between waste collections, saving money, fuel and traffic congestion;
- in the harbour, 150 "ship to grid" connection points allow cargo vessels and river cruisers to link to the power grid and switch off their diesel generators as soon as they dock;
- a smart building, the ITO Tower (Figure 8), which analyses its utilities consumption and usage patterns to identify potential for saving energy and lowering its carbon footprint;
- smart meters installed in 500 homes and businesses, with additional feedback on energy consumption sent via mobile phone;
- smart plugs to automatically dim or switch off unused appliances and lights;
- street lighting uses energy-saving lamps that can be dimmed at quieter times of the night[20].

Another Amsterdam smart city initiative is the installation of fuel cells in a 17th-century canal-side building, De Groene Bocht, in the city centre (Figure 9). Running on natural gas, the fuel cells provide all the electricity and heat used by the building; this use of fuel cells in an office setting is a world first. The project partners are Cool Endeavour, Eneco, Liander, GasTerra, Ceramic Fuel Cells Unlimited and De Groene Bocht[21].

A project named De Groenten uit Amsterdam ("Greens from Amsterdam") cultivates fruit and vegetables in abandoned buildings and offices in the city centre. Growing plants in tall stacks under red and blue LED lighting, these "indoor farms" yield organic produce with low consumption of water and energy[23]. Energy and CO_2 emissions from transport are saved and the citizens of Amsterdam can have fresher and healthier food.

Danish smart cities

Several Danish municipalities have become interested in smart city projects. To a large extent these have been based on activities begun in the run up to the UNFCCC COP 15 meeting in Copenhagen in December 2009, when many cities launched their own voluntary climate strategies. Many of the initiatives included both mitigation and adaptation. On this basis it was in many cases straightforward to continue working on smart city strategies, which compared to most climate plans have a broader focus on sustainable development, transport, housing and energy technologies.

The Danish activities have also included partnerships with industry through the Copenhagen Cleantech Cluster[24]. One important outcome of this was the conference Smart Cities – Smart Financing (3 May 2011), which discussed how Danish companies could focus more on large emerging economies[25]. The key conclusions were that there is great potential for market development in accordance with sustainable development principles, and that Danish technologies for buildings, heating, cooling and smart grids could be key components. Such developments should also be supported by green finance and new forms of collaboration and partnerships.

Figure 8

The ITO Tower project tested which technologies and management approaches were best at making office buildings more sustainable on a large scale. Photo: Roberto Rocco.

Copenhagen

The City of Copenhagen aims to make Copenhagen a sustainable and smart city, and has a strong focus on energy, climate change and broader environmental issues. The city has developed a rather ambitious climate change strategy, and also has a plan for green growth and smart grids by 2025. The city aims to reduce CO_2 emissions by 20% by 2015, and to be completely CO_2-neutral by 2025. In its plans to create a smart city the municipality is focusing on the need for a broad and integrated plan, where actions in different sectors such as buildings, transport and power production are co-ordinated and support each other. The municipality also emphasises the need to work closely with the private sector and research institutions to achieve its aims in the best possible way.

Figure 9

Fuel cell plant installed in De Groene Bocht, a canal-side house in Amsterdam now used as offices.[22]

The plans cover four main areas: green energy consumption, green energy production, green mobility, and adapting to climate change. The focus is on reducing CO_2 emissions, innovation, green growth, economy and partnerships.

As part of its climate change and smart city plans, Copenhagen intends to create "incentives for green growth and … sustainable development in the municipality of Copenhagen and the Øresund region; markets for green solutions; innovation; development and demonstration of new solutions (green lab); new financial and organisational forms; [and] partnerships between research, private and public stakeholders". It is worth noticing that the municipality aims to create a good framework for households, businesses, and investors, and at the same time is trying to make its own business more sustainable. For instance, there is emphasis on renovation and energy savings for public buildings, and the proposed Municipal Plan 2011 says that 85% of the municipality's vehicles should run on electricity or hydrogen by 2015.

In several respects Copenhagen has already come far in terms of sustainability. For example, almost every household is connected to the district heating network and 55% of citizens cycle every day.

Copenhagen is a city in development, and in the new parts of the city now being planned and built there is a strong focus on sustainability in a broad sense. This of course makes it easier for Copenhagen to develop as a smart city, as it is easier to integrate such ambitions from the very beginning. An example is the urban development project in Nordhavn – the North Harbour – which even has the working title The Sustainable City for the Future (Figure 10). The vision for this part of the city is that it should be eco-friendly, vibrant and dynamic, a place of sustainable mobility, a city by the water, a city for everyone. It is also intended to become a prototype smart city. More specifically, the plan is to develop and test new ideas for effective, intelligent, and environment-friendly power, heating and water supply, in an integrated manner[26].

Copenhagen also has a smart grid strategy for intelligent electricity consumption, in which factories, the service sector and private households will communicate interactively with the grid. The main components of the smart grid is that a market balances production with demand; power lines at different voltages distribute power efficiently; intelligent appliances and electric vehicles react to market conditions; and special equipment stabilises the grid to ensure high-quality power.

The Copenhagen plan emphasises the creation of incentives to get power consumers involved. A number of demonstration projects will first be used to show how specific technologies and solutions can support green growth. Once this is done, the next step will be to consider business partnership models and financial mechanisms, including public-private partnerships (Nordhavn, 2011). The proposed Municipal Plan 2011 foresees that by 2012 an agreement will be in place for a smart grid in Nordhavn.

Smart grids are not restricted to smart cities, so the two concepts overlap. The smart city concept, of course, is broader than the power system and also includes heating systems (district heating), water, wastewater and transport (see also Chapter 7).

Kalundborg

Kalundborg has only around 50,000 inhabitants, yet as the site of Denmark's largest power plant it produces 10% of the country's electricity and 9% of Danish CO_2 emissions. Kalundborg is also home to Denmark's second-densest industrial cluster, and half the city's CO_2 emissions result from the production of heat that is ultimately wasted in factories.

Working with companies in the industrial cluster the municipality has already set up a range of initiatives based on what it terms Industrial Symbiosis, in which participating companies use each other's waste products and by-products. Companies who buy and use other firms' surplus heat, for instance, already reduced CO_2 emissions by 240,000 t/y. Symbiosis also allows approximately a third of the area's water consumption to be re-used and recycled; slurry from municipal water treatment plants is used in soil cleaning processes; the removal of sulphur dioxide from flue gas at the power plant yields gypsum that is used to make plasterboard; yeast that is a waste product from insulin production is used as pig feed; and a waste product from industrial water treatment is turned into fertiliser. Several more plans for symbiosis to reduce environmental impacts are in the pipeline[27].

Seemingly as a natural progression from Industrial Symbiosis, Kalundborg has developed a smart city vision. Current plans involve working with public and private enterprises to plan energy use, a climate partnership with DONG Energy, an energy service company (ESCO) agreement with Schneider Electric and a memorandum of understanding with the smart grid specialist Spirae Inc. Over the next few years the municipality will collect data, model and simulate the energy system and carry out scenario analysis, with city planning as the eventual aim. The sectors expected to be part of the analysis are buildings, heating and cooling, electricity, transport, and industry[28].

Describing its climate partnership with Kalundborg, DONG Energy points out that to accomplish its objective of moving from 15% renewables to 85% renewables in its portfolio in a single generation, the company needs to develop and test new energy systems under realistic conditions.

Vejle

The municipality of Vejle is addressing its goal of becoming a smart city through a broad development strategy. Smart City Vejle aims to grow in areas including competitiveness, transport, the economy, communications, renewable resources, education and exploitation of human resources, quality of life, and citizens' participation in city administration and development. The Smart City Vejle project aims to kick off a variety of digital development projects that will help the municipality to provide better services for its citizens.

According to the project's website (www.smartcityvejle.dk) there are currently five focal areas: culture and tourism, e-learning, e-administration, health, and inspiration. It seems that Vejle's vision of a smart city is broad, and does not relate specifically to the energy system, or to smart grids for that matter.

SmartCityDK

Danish construction firms, architects, consultants and education and research institutes in Northern Jutland have established a network dealing with smart cities, SmartCityDk.dk, that aims to facilitate business development, innovation and exports. The focus is on new models to generate new knowledge, partnerships and business to support smart concepts for buildings; examples are "smart-dynamic" buildings and intelligent building materials with properties such as improved heat storage. One of the main

Figure 10

Nordhavn: A new sustainable quarter planned for Copenhagen's north harbour.
Illustration: The architectural firm COBE in collaboration with By & Havn.

aims is to establish collaboration between the business and research sectors; the network includes companies representing more than 43,000 employees and organisations representing more than 300 researchers.

The network's main activities right now are virtual and physical experimentaria, a centre for competence development, and several workshops on specific topics relating to construction and building management systems.

Conclusions

Discussions of climate change mitigation and renewable energy in the years to come will pay increasing attention to cities. One of the main forums for knowledge creation and exchange is the EU SETP, which has already created important EU-level alliances including research networks, industrial networks and the forthcoming research programme on smart cities.

The Danish examples show how the idea of the smart city can create platforms for the establishment of networks and collaboration between businesses, research institutions, local government and other partners, and so establish a good basis for innovative solutions and knowledge sharing. Many of the initiatives are spin-offs from other platforms such as the climate change plans in Copenhagen. Other initiatives like that of Vejle are inspired by a broad sustainable development agenda with economic, social, and environmental dimensions. These activities create nuclei that will form bases on which large city-wide projects can be built.

As noted above, the EU climate change mitigation targets for 2020, 2030 and 2050 are highly challenging. Radical innovations and a complete transformation of the energy system are needed to meet these challenges, and this in turn will require the integrated design and management of urban energy systems, as well as a parallel change from a single-technology to a multi-technology perspective.

As all these developments require new infrastructure, the timeline for project planning and implementation is of the utmost importance. In other words, it is necessary to start projects now if we are to complete the roll-out of smart cities by 2050. Furthermore, the transformation process for cities requires strong stakeholder involvement to develop joint visions and roadmaps taking in the technical, financial, policy and legal dimensions. The stakeholder process to involve all the relevant actors must cover a wide range of knowledge and needs, while remaining committed to the vision and the roadmap. The roadmaps and action plans serve as umbrellas for the various pilot projects, which must contribute to the chosen energy strategy whether they are privately or publicly financed. User involvement is expected to create a learning environment for technology acceptance and a basis for the adaptation of technology, implementation methods and business models.

The various smart city initiatives have not yet created a great deal of investment or changes to existing energy systems. At the moment they act simply as platforms for the development of ideas, business models and innovations. This is understandable given the large investments needed to create smart cities, and the current experimental state of most smart grids and intelligent energy systems.

Once all the necessary networks are in place, however, let us begin to invest in transforming our cities into smart cities. If we are to reach our ambitious targets for greenhouse gas emissions, the development of low-carbon cities is essential.

Buildings for smart cities

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Compilers of energy statistics normally divide final energy demand into four sectors:
- industry
- transport
- households
- services.

Households and services together are often referred to as the buildings sector, or simply buildings. Buildings are responsible for as much as 38% of all energy demand in the EU[29] and 40% in the USA[30]. On average, space heating accounts for two-thirds of the energy used in residential homes in the EU27[31], and in Denmark the proportion is almost 85%.

The European Commission has set a target for 2020 of cutting EU primary energy use by 20% compared to "business as usual" projections. However, recent estimates suggest that the EU is on course to achieve only half of the 20% objective. Responding to a call by the Council of Europe, the Commission presented a new Energy Efficiency Plan[32] in March 2011.

The new plan targets mainly buildings because this is where the greatest energy-reduction potential lies. The plan focuses on instruments to trigger the renovation of public and private buildings and to improve the energy performance of the components and appliances used in them. Since publicly owned or publicly occupied buildings represent about 12% by area of the EU building stock, the plan is to promote the public sector as an example. The plan proposes to accelerate the refurbishment rate of public buildings through a binding target for public authorities, and to set energy efficiency criteria in public spending. It also foresees obligations for utilities to help their customers use less energy.

Net-zero energy buildings

Net-zero-energy buildings (NZEBs) sound like the ultimate solution to the problem of high energy demand in the buildings sector. Many companies claim to be working towards NZEBs, or even to have created them. There are many different definitions of "zero energy"[33,34], however, and the degree of success depends in part on the definition chosen by the designers.

An NZEB is a building with greatly reduced energy needs. In such a building, the efficiency of energy use is high enough that the small excess of demand over supply can be made up by renewable energy (RE) technologies installed in or on the building. An NZEB therefore produces on average as much electricity and heat as it uses, or more, and exports any excess to the electricity or district heating grid.

There is a mutually beneficial relationship between an NZEB and the grid. By providing an outlet for surplus energy, the grid allows the building to accumulate energy credits that can be paid back at a future time. From the grid's point of view, the NZEB itself acts as a storage system, for instance to buffer intermittent supply from renewable sources. Achieving an NZEB without a grid is possible in principle, but would be very difficult in practice, since current energy storage technologies are still quite limited.

Table 2 classifies the various options for supplying RE to NZEBs.

The energy-reduction measures of Option 0 in Table 2 are a prerequisite for any NZEB, but in themselves they characterise a low-energy building, not an NZEB. Energy sources that cannot be commoditised, exported and sold – such as passive solar space heating, solar thermal air heaters, daylighting and natural ventilation – are considered to be demand-side technologies contributing to energy efficiency, but not on-site sources of RE in the context of NZEBs.

Option 1, on the other hand, covers RE from sources within the building footprint that can be exported whenever it is not required by the building itself. When this energy is used internally, direct connections to the building's electricity or HVAC system minimise transmission and distribution losses. Typical Option 1 technologies include PV and solar thermal systems; building-mounted wind turbines may also have limited application. Building-mounted RE technologies are preferable because the collection area can be guaranteed to be available over the life of the building.

Option 2 addresses RE generated on the building site but not within its footprint or mounted on the building. Typical strategies include PV systems mounted on sunshades in car parks, wind turbines in neighbouring fields, and ground-mounted solar hot water systems. Biomass harvested from the site and used in the building (or exported) is also considered an on-site RE source as long as the resource is renewable over the life of the building.

Buildings that use a lot of energy typically do not have enough area for RE collection within their site boundaries to qualify as NZEBs under Option 2. Examples are hospitals, laboratories, supermarkets, and especially skyscrapers in densely populated urban areas. Options 3 and 4 therefore introduce RE from sources beyond the site boundary to offset the building's energy use.

Under Option 3, a building could qualify as an NZEB by importing sources of RE and using these to generate energy on site. Examples are wood chips or pellets, waste vegetable oil, biodiesel and bioethanol.

Option 4 addresses the buying-in of RE generated off-site from an external source. However, a building that purchases all its RE has less incentive to reduce consumption. This implies that a building could qualify as an NZEB even if it directly uses more energy than necessary, thereby reducing the amount of RE available for useful purposes elsewhere.

Sustainable buildings

Although energy is central to sustainable buildings, it is not the only issue. Other aspects to consider when assessing the sustainability of a building include water use, the internal environment (health and well-being of the building's users), environmental pollution, transport, materials, waste, ecology, economy and management processes.

Of the various assessment methods and rating systems for sustainable buildings, the most used are:
- the American LEED system
- the British BREEAM system
- the Japanese CASBEE system
- the French HQE system
- the German DGNB system.

The Danish Green Building Council recently chose the DGNB system as the official assessment method for the sustainability of buildings in Denmark[35]. This is good news for building investors in Denmark since a common assessment method allows different building projects to be compared directly.

Table 2
Hierarchy of supply options for renewable energy in net-zero-energy buildings.[33,34]

Option number	NZEB supply-side options	Examples
0	Reduce site energy use through energy efficiency and demand-side renewable building technologies. This option is a prerequisite for an NZEB and characterizes a low-energy building.	Daylighting; insulation; passive solar heating; high-efficiency HVAC equipment.
On-site supply options		
1	Use RE sources available within the building footprint and connected to its electricity or hot/chilled water distribution systems.	PV, solar hot water and wind turbines located on the building.
2	Use RE sources available at the building site and connected to the building's electricity or hot/chilled water distribution systems.	PV, solar hot water, low-impact hydro and wind turbines located in car parks or other nearby open space, but not physically mounted on the building.
Off-site supply options		
3	Import renewable fuels to generate energy on site, connected to the building's electricity or hot/chilled water distribution systems.	Biomass, wood pellets, ethanol or biodiesel brought in from elsewhere, used on site to generate electricity and heat.
4	Buy in enough energy from off-site renewable sources to maintain NZEB status.	Utility-scale wind, PV, emissions credits or other green purchasing options. A building could also negotiate with its power provider to install dedicated wind turbines or PV panels at another site.

The weighting factors for the different measures of sustainability may depend more on politics or common sense than on science. In an office building, for example, the salaries of the employees might add up to 100 times the cost of heating, cooling and ventilation. Since an uncomfortable working environment harms job performance, we could argue that a building's indoor climate should score much more highly than its energy performance.

The transparency of the building market across national borders is still limited, since different countries currently use different rating systems for sustainable buildings, as indicated by the five different methods listed above. To address this problem, the European Committee for Standardisation has formed a Technical Committee for Sustainability of Construction Works (CEN/TC 350)[36]. This body is developing voluntary standards for assessing the sustainability of new and existing construction works and for environmental product declarations in construction products. These standards will be generally applicable and applicable to buildings over their complete life cycle. The standards will set out a harmonised methodology for assessing the environmental performance and life-cycle cost performance of buildings, as well as quantitative measures of the healthiness and comfort of buildings.

Smart buildings

There is an increasing interest in "smart buildings", which are designed to minimise their lifetime use of energy and other resources. Rather than being managed separately, systems in a smart building inter-operate to a high degree, aided by information technologies. Large numbers of sensors, for instance, can monitor everything from motion and temperature to humidity, precipitation, room occupancy and light levels. Actuators and smart materials can then react to these measurements, ensuring that resources are used only when needed.

A central challenge for any smart building is the potential conflict between indoor environment quality and energy use. A good indoor environment requires buildings to be well ventilated with fresh air and heated or cooled as necessary. The problem is that ventilation, heating and cooling may increase energy demand, to the extent that in the name of energy efficiency buildings are made more airtight and exterior walls and windows are thermally insulated. The question is how to make buildings energy-efficient without compromising the indoor environment.

The answer lies in integrated design[37]. Smart buildings are optimised not for one parameter at a time, but in an integrated way that takes account of all the issues affecting the building, even when these initially seem to contradict each other.

An example of an energy-efficient way to heat or cool a building is the use of water circulating through pipes embedded in floors, walls or ceilings ("slab heating" and "slab cooling"). Such systems use radiation rather than convection as the main method of heat transfer within the room itself. The circulating water needs to be only a few degrees warmer or colder than the desired room temperature ("low-exergy" systems); this increases the efficiency of equipment such as heat pumps and maximises the potential for RE sources such as ground-source heat exchangers, evaporative cooling and adsorption heat pumps.

The thermal storage capacity of the building itself can also reduce peak cooling loads and allow much of the heat to be rejected at night, when ambient temperatures are lower. Apart from their lower energy use, slab heating and cooling systems take up less space than the bulky ducts and fans needed for traditional air conditioning.

The International Centre for Indoor Environment and Energy at the DTU Department of Civil Engineering has been involved in several building projects using this technology, including Bangkok International Suvarnabhumi Airport (Figure 11) and the Copenhagen Opera House.

Through a joint programme run by the European Commission and the Association of Southeast Asian Nations (ASEAN), the Centre was also involved in a demonstration project in Malaysia in which slab cooling will be used in a net-zero-energy office building. In this case the building uses PV to generate its own power during the day, with surplus power exported to the grid and bought back at night.

A challenge with radiant cooling systems in countries like Thailand and Malaysia, where both temperature and humidity can be high, is to avoid condensation. Traditional air conditioning suffers less from this problem because it dries the air as well as cooling it. Another difficulty is the small temperature difference between day and night, which makes the use of mass less effective in averaging thermal loads.

With proper design, however, it is entirely practical to use a combination of high-temperature radiant cooling with a scaled-down air conditioning system. In this case the air conditioning is sized to provide the necessary ventilation and dehumidification rather than the total cooling load.

From building components to smart green buildings

A recent innovation study showed that energy efficiency has become the most important driver of innovation in the Danish supply chain for windows[38]. All the companies in the window supply chain now expect increasingly strict policies for energy efficiency to be introduced, and believe energy efficiency to be a key and lasting profit opportunity. Also other environmental concerns are high on the agenda in the companies.

There is an interesting strategic change among the largest Danish window companies, which are shifting from developing building components (windows) to increasingly acting as core developers of smart green buildings (Figure 12) They are taking on new roles as system integrators in the window chain as they engage in high-tech systemic eco-innovations for smart green buildings, integrating smart, multi-coated windows with systems for passive lighting and ventilation, sunscreens, solar energy and LED lighting. The green demo house projects introduced in many Danish municipalities act as important drivers for the development of more advanced smart solutions for green buildings. These are mostly for new builds, however, whereas renovating the existing building stock to create smart buildings remains a great challenge.

Figure 11

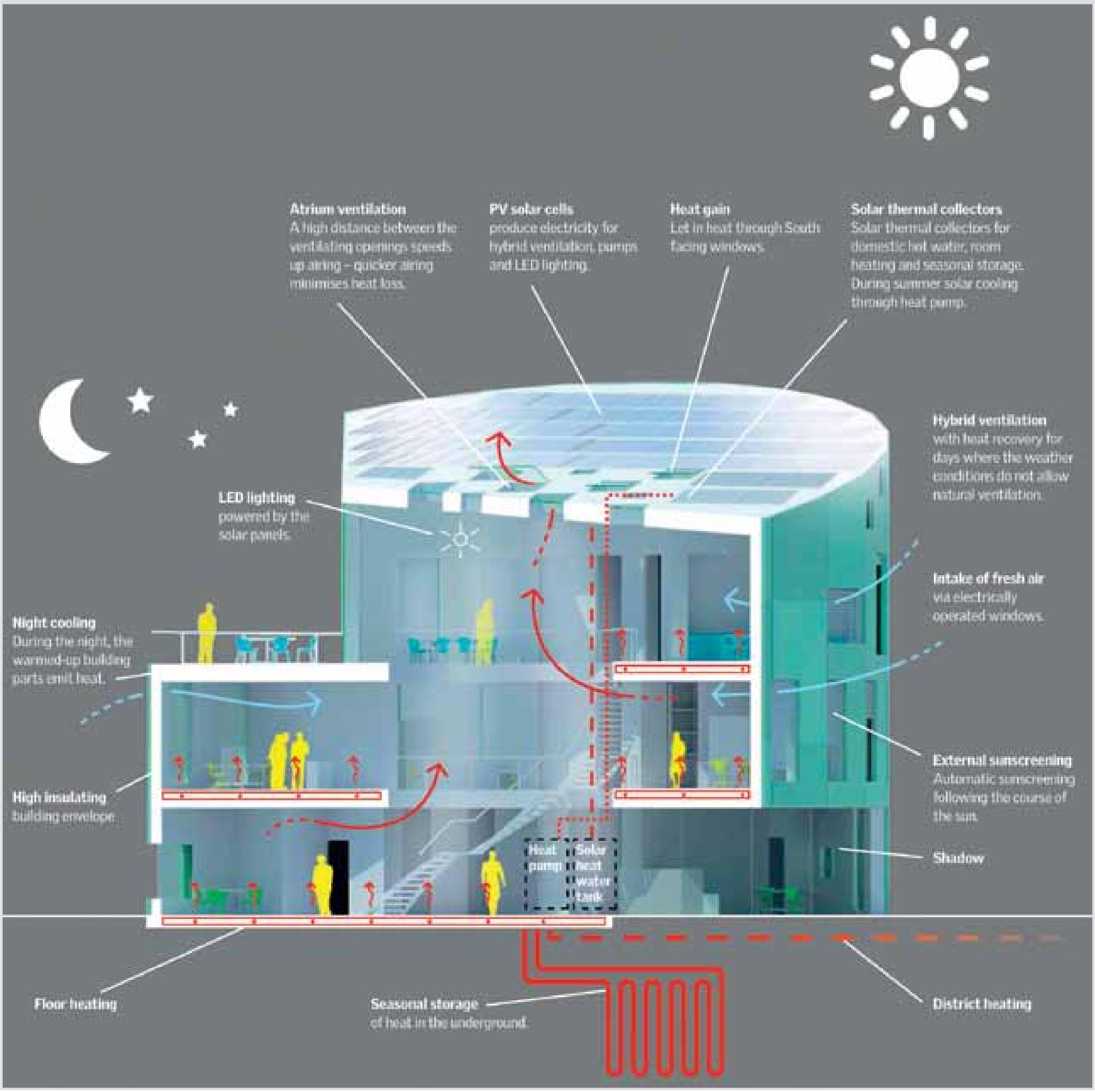
Bangkok International Suvarnabhumi Airport. Picture: Wikimedia Commons.

Denmark's first public CO_2-neutral building is the Green Lighthouse. It is the result of public-private cooperation between the University of Copenhagen, the Ministry of Science, Technology and Innovation, the City of Copenhagen, VELUX and VELFAC.

The study referred to above was focused on green nanotechnology in the Nordic construction sector[38]. The researchers found that although nanotechnology has seen little uptake in traditional construction, where rates of innovation tend to be low, it is quite widespread in developments relating to improved environmental performance.

Figure 12

Green Lighthouse was built in 2009 before COP15.
Illustration by CHRISTENSEN & CO arkitekter a/s.



In the window supply chain, all the innovations based on nanotechnology were green, though not every eco-innovation used nanotechnology.

Interestingly, the study showed that the considerable contribution of nanotechnology to eco-innovation in the construction sector is not widely known. This seems mainly to be related to concerns about the risks associated with nanotechnology. At the start of this decade companies promoted nanotechnology widely in their marketing activities, but in recent years they have become more cautious.

Overall, the study illustrates the rise of the green market and the increasingly progressive strategies used by companies which leads to still smarter and more systemic solutions for green buildings[38,39].

Conclusions

In this chapter we have described a number of different approaches to cutting the large amount of energy used in buildings – close to 40% of total final energy consumption in both the EU and the US – and to replacing fossil-based energy with RE in the buildings sector. However, there are several obstacles to progress in reducing energy use and CO_2 emissions in the buildings sector.

One of these is the rate of renewal of the building stock. The average yearly new-build rate is estimated to be just 1.0–1.3% of the existing building stock (there are approximately 210 million buildings in Europe, with around 53 billion m^2 of usable indoor space for all types of human activity)[40]. The vast majority of both existing and new buildings meet only the minimum requirements of national building regulations, which do not even come close to NZEB performance.

Given the relatively low number of new buildings, the bulk of the potential lies in renovating the existing building stock. However, major renovations take place on average only every 30–40 years. If the window of opportunity offered by a major renovation has passed, implementing RE or energy-efficiency technologies becomes more expensive and difficult. It is therefore crucial that a large proportion of renovation projects are "deep energy" renovations that reduce energy use by 60–90% and use RE for the remainder. Currently, however, most renovation projects probably achieve energy reductions of only 15–20% and ignore RE.

Another obstacle is that energy-efficient buildings are often technically demanding, and there is a lack of appropriate training for architects, engineers, auditors, craftsmen, technicians and installers, notably for those involved in refurbishment. Today about 1.1 million qualified workers are available in the EU, while it is estimated that 2.5 million will be needed by 2015. The European Commission is launching the BUILD UP Skills: Sustainable Building Workforce initiative to address this shortfall[32].

The policy attention to energy efficiency and its link to buildings have never been greater. But, although there is a potential to greatly reduce our energy demand and CO_2 emissions, while at the same time improving the quality of living and working in smart buildings, it is obvious that especially the more radical and systemic improvements will not come through a "business as usual" approach. Concerted action is required by a range of actors – legislators, building professionals, investors and homeowners – for this potential to be realised. A notable step in this direction has been taken in the Plan C project[41] supported by EU's regional fund and the Capital Region of Denmark for the period 2010-2012. In this project, 35 partners including 8 municipalities, main companies in construction and cleantech and leading research institutions have joined forces in addressing the many different challenges related to performing efficient energy renovation of publically owned buildings.

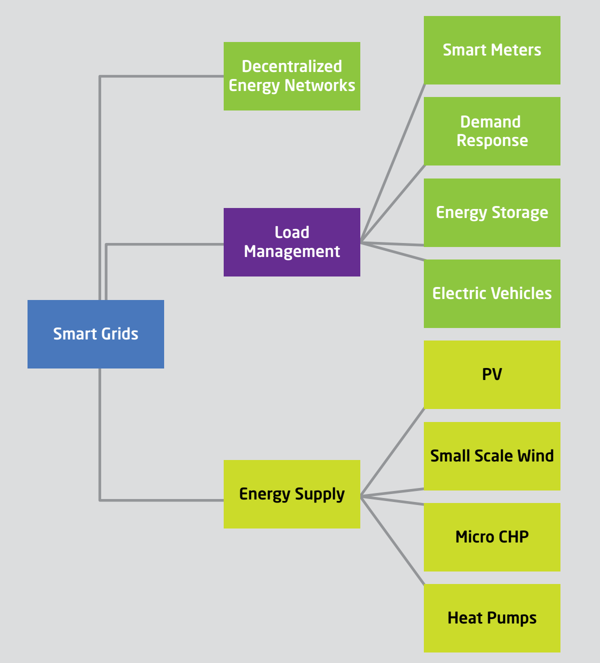
Energy networks

Argyrios Altiparmakis and Peter Meibom, Risø DTU

In the face of growing urban populations in most countries, it is important for new cities to adopt smart energy networks that allow greater energy efficiency and greater flexibility in energy use. A breadth of technologies are being developed to achieve this goal, reflecting the fact that there are multiple aspects to making grids smarter. Most approaches, however, involve applying information and communications technology (ICT) to energy networks. The current energy networks are somewhat antiquated, having mostly been built 30 years or more ago. Introducing ICT into those networks allows better communication between different parts of the grid as well as between the grid, its operators and its customers.

The smart grid also allows room for the development of decentralised or localised energy production and consumption. This has multiple advantages. Primarily, it can improve energy efficiency because long distribution networks are no longer required, and energy can be produced close to the points of consumption. This implies new, decentralised methods of production and efficient control mechanisms to manage energy in small local networks. The production technologies most commonly suggested are solar, micro-CHP, wind and heat pumps, so the new smart city grid will get much of its energy from renewable sources[42,43].

Figure 13
Smart grid components for urban environments. In any power system supply needs to balance demand at all times, so techniques allowing demand to be adjusted to better match the intermittent supply from renewable energy systems (RESs) will be necessary.



An additional benefit from the energy technologies and localised structures that characterise smart grids is the ability to supply the heating network with waste heat from electricity generation. This is already done with great success in Scandinavia, especially in the district heating systems of cities like Copenhagen. The resulting integration of the heat and power networks can provide great savings in energy use and cost.

An extension of this idea is to bring grids for district cooling (see below) and natural gas into the existing networks. At the moment gas is mostly used for cooking, space heating and hot water. In the future it could also be used to fuel micro-CHP plants that will reduce peak loads on the central power grid as well as providing heat.

The smooth running of energy networks based largely on renewable sources will require policies and technology to manage demand response. Metering, price displays, sophisticated control systems, localised energy storage and real time-updates on power usage and pricing are all important to the development of smart cities. In any power system supply needs to balance demand at all times, so techniques allowing demand to be adjusted to better match the intermittent supply from renewable energy systems (RESs) will be necessary (Figure 13). Grid-connected electric cars can also help to smooth energy peaks and troughs by storing power.

To summarise, smart cities will be characterised by:
- decentralised production of energy mainly from renewables and micro-CHP;
- greater energy efficiency and integration of energy networks, mostly achieved through the lower transmission losses associated with local energy systems;
- energy management systems that can balance supply against demand and react successfully to grid changes;
- demand response technologies and policies that encourage consumers and grid participants to use energy in ways that are optimal at system level; and
- affordable and efficient heating based on the synergy between decentralised, renewable electricity production and district heating/cooling networks.

Smart distribution networks

On the production side, several renewable energy technologies are well-adapted for cities. PV panels on rooftops, small urban wind turbines and micro-CHP plants running on fuels including biomass can underpin the shift in energy production from fossil fuels to renewables and from centralised to decentralised production. These technologies are flexible in that they can be installed in small spaces and be controlled locally to provide electricity and heat to areas ranging from single buildings to entire city districts.

The production of energy locally at the household level can allow electric vehicles (EVs) to be introduced into the energy system. EVs supplied from renewable power sources considerably reduce emissions and oil dependency compared to conventional cars. A potential problem, however, is large spikes in power demand in the evening, when people return from work and plug in their EVs.

A smart energy network must therefore be able to handle EVs, possibly by providing extra production capacity at peak times and certainly by shifting demand by widening the time window over which EVs are charged. In fact it should be possible to use plugged-in EVs as short-term power sources to increase grid flexibility rather than reducing it, though this will require advanced techniques and strategies for load management.

Heat pumps are another technology that can be incorporated into smart networks. By taking most of their energy from wastewater or other waste streams[44], heat pumps can be clean and sustainable sources of heat. Large-scale heat pumps are already used in several parts of the world, including Denmark, with great success[45].

Load management control

Any energy system that incorporate renewables, EVs and other innovative technologies on a large scale faces the challenge of matching supply to demand. Since renewables and EVs add unpredictability and variability to the system, system stability may be threatened unless load management mechanisms are added[44].

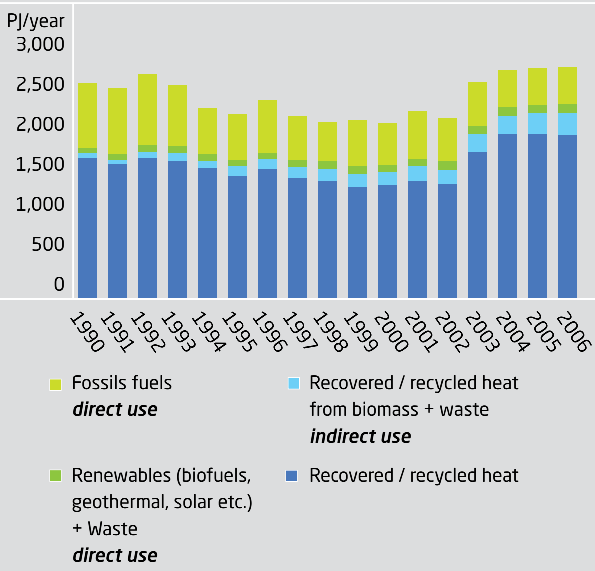
The first step towards better load management control should be smarter metering. Both producers and consumers benefit from being more conscious of the energy consumed by different processes and devices: operators can control their energy systems more efficiently, and consumers can manage their energy-intensive consumption in ways that are more timely and economical.

Another way to improve load management is a more sophisticated control architecture that allows bottlenecks and energy congestion to be handled more effectively. Since the output from RESs such as solar panels and wind turbines varies according to the time of day and the weather, energy supplies can show both large excesses and large deficiencies. Local energy storage systems and control mechanisms to better manage these events could improve network performance considerably.

Finally, it is important to introduce demand response into the system. Demand response can be voluntary, automated, or both. Most consumers currently cannot see the cost of their energy use and typically pay the same price no matter when they use that energy. Real-time markets and information systems that tell consumers when electricity is cheap or expensive could cut peak demand, overall consumption and consumers' bills because people would turn off some appliances when demand – and prices – are high.

Some appliances could also be programmed to turn on and off depending on the state of the energy system or the cost of power. Fridges and washing machines, for instance, could reduce their power consumption or switch off completely for short periods without causing their owners

Figure 14
Heat sources for district heating across the EU from 1990 to 2006.[45]



much inconvenience. EVs could do the same while on charge, and already-charged EV batteries could feed energy back to the grid during peak load periods, increasing the stability of the system.

District heating and cooling

District heating refers to the use of CHP plants, dedicated boilers and other heat sources to provide space heating to large urban areas. The aim is to provide heat cheaply and efficiently over dense areas while minimising resource waste.

District heating is a speciality of northern Europe: for instance, almost 90% of Copenhagen's residents get their heating in this way[45]. District heating can exploit "waste" heat from industrial processes such as power generation and waste incineration, as well as recovering heat from the environment using heat pumps powered by cheap renewable energy.

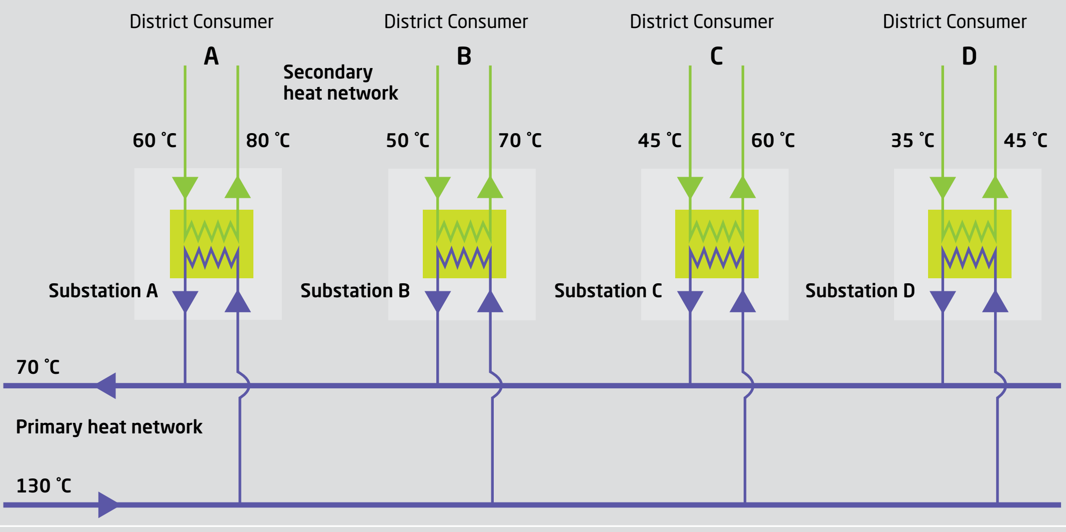
At the moment most district heating is provided through CHP, as a by-product of power generation. A smaller fraction comes from renewable energy sources and plants burning biofuels (Figure 14).

Wider use of district heating would lead to a marked improvement in the efficiency of energy use. Well over half the energy used to generate electricity in centralised thermal power plants is wasted, while at the same time around 50–60% of our total final energy consumption is used to heat buildings[45]. Matching up sources of "waste" heat with users of heat, as district heating does, improves overall efficiency and reduces total energy use.

District heating systems can use surplus power generated by small decentralised renewable resources, such as solar rooftops, in nearby buildings; during periods of high production this energy might otherwise be wasted. Figure 15 is a schematic of a large-scale district heating system.[45]

District cooling follows a similar pattern, supplying chilled water to a network of users (Figure 16 [46]). Cooling can be obtained directly from seawater or groundwater – a promising approach in hot countries whose power grids may struggle to match demand from electric air conditioning. Alternatively, cooling can be provided indirectly via heat pumps or absorption refrigeration systems that take most of their energy from the environment, industrial waste heat or leftover heat from district heating. Even when it is powered entirely by electricity, thanks to economies of scale district cooling is more efficient than a large number of individual air conditioning systems in separate buildings[46].

Figure 15
A conventional district heating network.[45]



Although district cooling is not yet widely used, its technical principles are similar to those for district heating, with networks of pipes to distribute chilled water. Like district heating, district cooling also brings the advantage of centralised maintenance.

District cooling schemes are currently operating in the Middle East and have been successfully tested in European countries including Sweden and the Netherlands[47].

PV installation and urban wind turbines provide low-cost electricity when power demand is low, such as during the summer months in Denmark. This cheap power can be used to produce heat either directly or by driving heat pumps in district heating systems[48], so achieving the objective of producing both electricity and heat renewably and in a decentralised fashion. In the winter, when power prices are high, micro-CHP plants can take over to produce both power and heat.

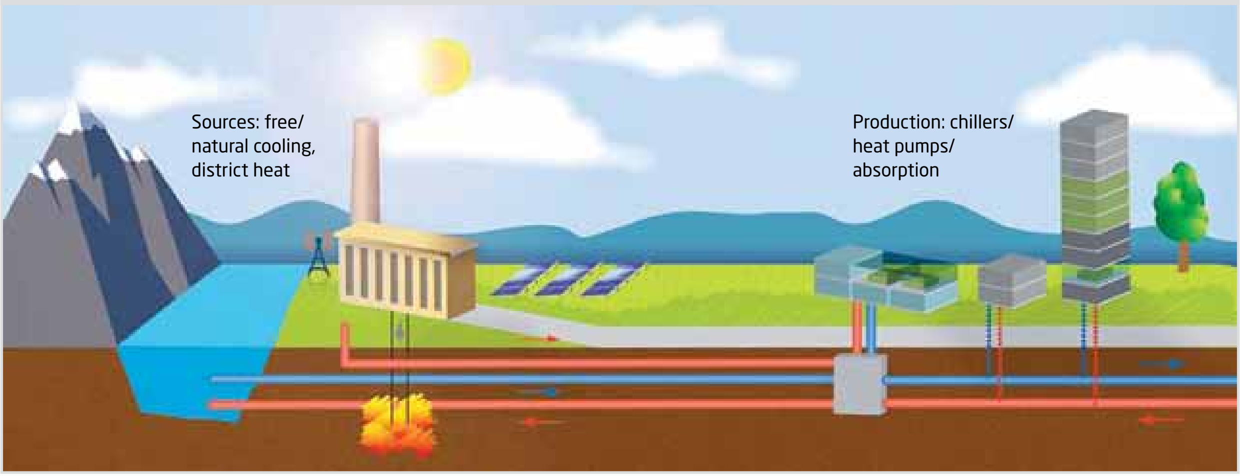
District heating and district cooling both benefit from the inclusion of thermal storage. This can allow a smaller system to accommodate the same peak demand, and may reduce running costs by allowing the system to delay electricity use when prices are high.

Conclusions

This chapter has identified the main components of a smart energy network. Its architecture is based on three sectors: Changes to the energy supply side through the installation of PV, urban wind, heat pumps, micro-CHP plants and electric cars; changes to the demand side through an effort to implement measures that change demand patterns voluntarily or automatically; finally changes to network design leading to district level solutions and the integration of different energy networks. Conclusively, the smart energy network will be more local, combine different functions (heating, cooling, gas and electricity) and will be powered by renewable sources of energy.

Figure 16

Schematic illustration of a district cooling system.



8

Transport for smart cities

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The global megatrend of the last century's migration from rural to ever-larger conurbations has created immense gains to society through economies of scale and benefits from agglomeration. These include – other things remaining equal – a lesser need for transport because a bigger share of peoples' activities can be reached within the relative close distances of the city. However, urbanisation has also led to significant disadvantages, of which transport accounts for some of the most severe. Traffic accidents and emissions of air pollutants and noise take heavy tolls in terms of people killed and injured, although in many countries the situation has improved over recent decades. Two major issues, however, have proven very difficult to cope with, to the point where the problems they cause are not yet diminishing.

The first is traffic congestion. This has intensified in many places, apart from in recent years where traffic volumes have been reduced as a result of the financial crisis. Serious budget deficits in many European countries will mean less investment in transport infrastructure in the years to come and therefore bigger difficulties to meet growing transport demand by increasing the capacity of the network. As a result, there is a genuine threat that growing congestion and longer journey times will hamper the mobility of people and goods, especially around big cities.

The second issue is global warming. This is the tragedy of the commons of modern times[49]: the greenhouse gas (GHG) emissions of individuals and even many nations are insignificant, yet cumulatively they cause a huge problem for the whole world. The share of total GHG emissions attributable to transport is rising and may reach almost half by 2050[50].

The solutions to both of these challenges must come hand in hand. High mobility is considered a prerequisite for economic growth, and without growth it will be politically difficult to cut CO_2 emissions to the necessary extent if the price is significantly lower growth.

The UN Copenhagen climate change conference in 2009 agreed the principle of a dramatic reduction in global GHG emissions to limit global warming to 2°C. As one of the world's main GHG emitters, the EU will probably have to reduce emissions by 80–95% by 2050, with a cut of at least 60% in transport-related emissions[51].

Taking into account the likely increase in transport demand caused by continued economic growth, the average CO_2 intensity per passenger or per tonne-kilometre will have to fall by far more than 60%. Assuming for simplicity that transport grows at 1½% a year – somewhat below historical trends[52] – transport volumes in 2050 will be almost double those of today. An 80% reduction in CO_2 intensity will therefore be needed to reach the EU target.

Most independent cost-effectiveness studies point to improvements in existing vehicle technology as the cheapest way to achieve significant CO_2 reductions in the short to medium term. Some researchers even identify "no regrets" options with negative costs per tonne of CO_2 avoided – that is, there is a net benefit in terms of lower vehicle operating costs and environmental improvements apart from the GHG reduction[53].

However, even with optimistic forecasts for improvements in energy efficiency it is not likely that the target for 2050 can be met by technological development of conventional engines burning fossil fuels. The scale of GHG emissions reduction needed calls for more fundamental changes in the transport sector.

Road transport will have a principal role in this transformation for two reasons.

First, road transport accounts for by far the largest share of the total energy used for passenger and freight transport in the EU (85% and 44% respectively)[54].

Second, for certain other parts of the transport sector we currently do not have even a clear vision of realistic alternatives to fossil fuels. This is certainly the case for aviation and intercontinental maritime freight. This indicates that these sectors will be among the last to shift away from fossil fuels as their primary energy source.

A shift toward less energy-consuming modes of transport such as trains, buses, cycling and walking can lower total energy consumption to some extent and so make it easier to meet demand purely from renewable energy sources. More importantly, in cities a shift away from cars brings benefits in terms of reduced congestion, noise and air pollution, and makes the urban environment generally more "liveable".

The dominant role of passenger cars, however, makes it unrealistic to expect that shift to public transport, cycling and walking in general will be big enough to contribute significantly to the 60% reduction target. In Denmark, for example, a shift away from cars that would double the use of public transport would lower passenger car traffic by just 15%, which only matches the expected growth over the next decade[55]. Exploiting the full estimated potential for cycling to replace car trips would reduce the energy consumed by Danish cars by only 2–2½%[56].

A long-term solution to the climate change challenge therefore calls for a technological shift to new energy forms with radically lower life-cycle GHG emissions per unit of energy. At present there appears to be two main tracks for this transformation:

Biofuels in conventional internal combustion engines. These have the clear advantage that they can easily substitute gasoline and diesel in today's engines by minor modifications.

Electric propulsion, which has significantly better energy efficiency. To comply with the target of radically lower GHG emissions the electricity must be produced from non-fossil sources, or with carbon capture and storage.

Energy for electric vehicles can be stored either in batteries, or chemically – for instance as hydrogen – with fuel cells to convert chemical energy to electricity. The latter approach introduces extra conversion losses which reduce energy efficiency. In either case, more technological development in energy storage is needed before electric vehicles can replace conventional cars as the dominant mode in passenger transport.

Hydrogen has an advantage over batteries in terms of driving range because its energy density (measured as MJ/kg) is even higher than that of gasoline and diesel, although its high volatility makes storage technically complicated and costly. Making hydrogen from electricity (at present the easiest way to get hydrogen from renewable energy sources) and then using a fuel cell to convert it back to electricity involves two sets of conversion losses, so there is a considerable penalty in energy efficiency. Finally, hydrogen cars are still not ready for the market and their widespread use will require a retail distribution system for hydrogen.

The Achilles' heel of batteries, on the other hand, is their cost and weight. Both cost and weight per kWh of battery capacity have gone down over the last 5–10 years, and performance will most likely improve even more over the coming decade[57] if recent high oil prices continue. If that happens, electric vehicles can become financially competitive with conventional cars over their life cycles.

For the moment, however, the driving range of electric cars is only a fraction of that of their conventional counterparts. A network of stations for battery exchange or fast charging could compensate to some extent, but for at least the next 5–10 years pure electric vehicles[58] will be best suited for car users with mainly short trips, or as the second car in households with two cars. The first mass-market electric

Figure 17

"Cars of the future". From upper left: Nissan Leaf (electric), Mitsubishi i-MiEV (electric), Opel Ampera (plug-in hybrid).
From lower left: Honda Clarity (hydrogen), Lexus CT 200h (hybrid) and Toyota Prius Plug-in Hybrid. Source: Car manufacturer's media portals.

vehicles that are now appearing (Figure 17) will therefore probably sell best in urban areas where people live close to work, shopping and other daily activities.

Technologies for urban transport

Walking and cycling

In urban areas non-fuel-consuming transport should be encouraged to the highest degree possible from an environmental and resource perspective. Over short distances, walking and cycling are in several ways attractive alternative ways to get to work and to the shops and other daily activities: In addition to the environmental advantages, they promote health, are inexpensive and, not least, reduces congestion.

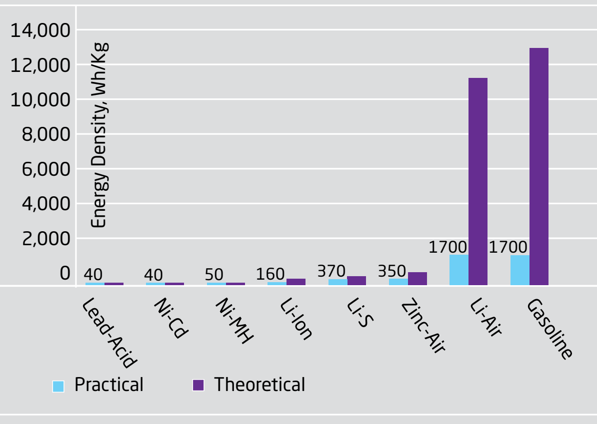
Walking and cycling can be promoted by well-designed traffic lanes that where possible give priority over motor vehicles, so as to prevent unnecessary stops. Close links between walking routes, cycle facilities and public transport encourage people to make longer journeys without resorting to cars.

Public transport

If the targets for GHG emissions are to be met and the forecasted supply-demand imbalances in the oil market dissolved, the future energy supply in cities is likely to be primarily electricity from wind turbines, solar panels and perhaps other renewable and non-carbon energy forms. Public transport in cities could easily be powered predominantly by electricity, which has the extra advantages of being quiet and causing no local air pollution. However, electricity for traction does not have to come from batteries and power lines; as discussed above, fuel cells can also be used.

Figure 18

Gravimetric energy densities (Wh/kg) for various types of rechargeable batteries compared to gasoline. The theoretical energy density (blue) is based strictly on thermodynamics. For Li-air batteries the practical value (orange) is an estimate. For gasoline, the practical value includes the average tank-to-wheel efficiency of cars[61].



Electric trains, trams and possibly buses using overhead power lines or live rails have obvious potentials for intra-urban transport. However, supplying these vehicles with electricity directly from generating plants would make existing rush-hour electricity demand peaks worse. At least some of the power supply for public transport could be uncoupled from the generators through some kind of energy storage. This can be done via large static energy stores, which could also serve users other than transport, or via batteries or synthetic fuel carried by each vehicle. However, as for batteries for individual electric vehicle the costs of these types of storage are not ignorable, and it is still too early to tell whether the economically efficient solution to the peak problem will rely mainly on storage solutions or time-of-day shifts of power demand.

Individual transport

Effective public transport systems may take over a large proportion of urban transport needs, and especially so in major cities where this is already the situation in many places. However, as described earlier, individual motorised transport will persist. Electric vehicles running on batteries or fuel cells appear today to be the most likely candidates for future traction technologies, but they still need more R&D.

Batteries still suffer from low energy density (Figure 18), long recharging times and loss of capacity over time. As a result, current battery-powered vehicles cannot store enough energy even for medium-length journeys and are limited to around 100 km per charge. Some suppliers of battery vehicles have announced longer ranges[59], but until this has been properly demonstrated by ordinary users there is room for doubt.

The driving range of a battery vehicle depends strongly on driver behaviour (in particular acceleration and speed) and driving pattern (such as the number of stops). In winter, the extra power needed to heat the car cabin, seats and windows permanently lowers the battery capacity as well as reducing the driving range.

Even after driving 50–80 km, batteries need a considerable time to recharge. Practical experience under Northern European conditions (including winter driving) is not very encouraging[60]. But it is generally believed that batteries will improve significantly in the coming years, in terms of both improvements to existing technologies and the development of completely new types. In the latter class lithium-air batteries offer huge potential, with an energy density matching that of gasoline, but need intensive R&D before commercialisation[61].

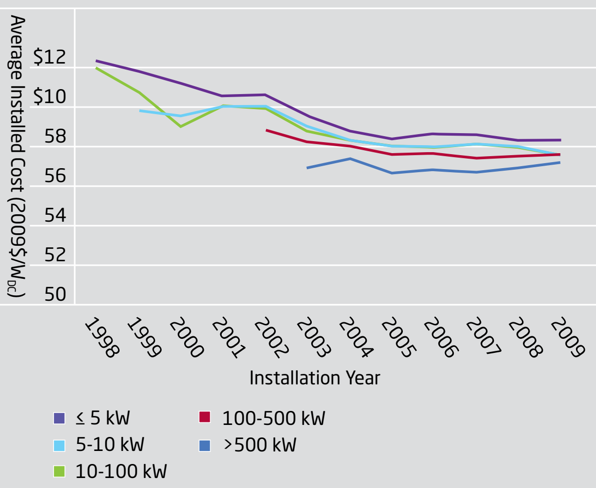
Fuel cells with an appropriate fuel – perhaps hydrogen – represent another traction technology with properties suitable for city use. The fuel can be stored in the vehicle at energy density one or two orders of magnitude higher than that of current batteries. Fuel cells are excellent at providing constant power for steady speeds, but they are not ideal for cold starts and rapid acceleration.

Batteries in combination with fuel cells thus seem to be the technically ideal solution for future cars in cities and even further afield. The drawback is cost, since there are two different technologies, each of which is expensive. However, prices have fallen over recent decades, especially for fuel cells, which over the last ten years have fallen from $12/W to $8/W (Figure 19). This trend is likely to continue as demand increases and mass production yields economies of scale.[61]

Energy for urban transport

Electricity clearly has the potential, either directly or indirectly, to constitute the basis for most of the energy used in urban transport once we have stopped using fossil fuels. Electricity can supply vehicle batteries directly, or can be converted to hydrogen by electrolysis near the point of use.

Figure 19
Falling fuel cell prices, 1998-2009.



The only real competitor to electricity in this respect is fuel produced from biomass, whose long-term role is difficult to predict. Questions of ethics and land availability are not encouraging for the development of biomass, though the ability to harvest large quantities of marine algae could change this situation.

Cities already use electricity extensively, which has obvious advantages in terms of offering an existing distribution net, when additional demand from transport will increase demand in the short to medium term. However, in the long term this will challenge the capacity of distribution systems. Many cities will need grid reinforcement to provide enough capacity for charging large vehicle batteries. Once this capacity is in place, however, smart charging and discharging of a large fleet of vehicle batteries could help the grid to manage fluctuations in the supply of renewable electricity.

One aspect that is often overlooked is that infrastructure costs for charging electric vehicles vary significantly with housing type. House-owners who keep their cars on driveways or in garages can charge them overnight using relatively inexpensive equipment. In cities, however, where the potential for short-range electric cars is biggest, many people live in apartments and park their cars on the road over night. Most apartment dwellers will need public charging points, which cost €5,000–10,000 per vehicle – roughly the same as the cost of the battery.

Hydrogen or other chemical fuels for fuel cells may be produced in large centralised plants, preferably outside urban areas, or in small local plants that might be placed within cities. Large centralised plants will probably be cheapest and also most effective in balancing the electricity system against supply fluctuations. In the latter case we can imagine that chemical fuels need not be transported into the city; instead, vehicles would use battery power within the urban area, while for longer journeys they would stop to pick up chemical fuel on reaching the city outskirts.

In the long term, electricity for transport may come to dominate the energy supplied to houses and apartments. This will happen as building insulation improves, household appliances require less power, and householders generate more of their own power from PV and micro-CHP.

Energy technologies for smart cities

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Smart cities must become champions of renewable energy and low-carbon technologies. As each of the world's megacities is inhabited by more than 10 million people, their energy needs are huge. Smart cities therefore need highly distributed energy supplies and to a large extent they should be self-supplying, to minimise the need for investment in transmission lines carrying electricity, district heating and cooling and natural gas from distant plants. This chapter gives an overview of the energy technologies that can meet these requirements.

Wind energy

Christina Beller, Peggy Friis and Peter Hauge Madsen, Risø DTU

The idea of erecting wind turbines in the built environment has emerged only in the last few years. As with other methods of producing renewable energy locally, it arose from a natural trend. Solar energy, for example, can be harvested in large central plants, but it is also ideal for decentralised use at or close to the point of use. Wind power is now following this route.

Large wind turbines have been installed onshore and offshore for many years and are well understood. In contrast, knowledge of how to design, position and operate small turbines has accumulated only slowly. Probably for this reason there is a wide range of designs: miniature versions of the traditional three-blade upwind horizontal-axis turbine, multi-blade "wind roses", downwind machines, designs with furling tails and rotors, and various types of the vertical-axis turbines often favoured by architects and city planners.

A small number of urban wind systems have been rigorously tested, notably in the UK[62]. The general conclusion is that energy production depends on the local wind climate, the precise location of the turbine, and how well the turbine design matches the available wind.

Urban wind background

Wind velocities onshore are lower than those offshore because the greater roughness of the land surface acts as an obstacle. Increasing roughness also means greater turbulence[63]. These effects are most pronounced in cities: compared to an open onshore site, a densely built environment has a greater roughness length, a lower average wind speed and a great deal more turbulence. Residential locations are also more demanding in terms of turbine safety, noise and aesthetics.

Table 3
Danish law demands type approval for small wind turbines. The number of designs registered is increasing fast.

May 2011	< 5 m^2	< 40 m^2	< 200 m^2	Total
Number of approvals	10	22	8	40
Certified /notified	10	6	3	19
Prototypes	0	16	5	21
May 2010	**< 5 m^2**	**< 40 m^2**	**< 200 m^2**	**Total**
Number of approvals	8	4	2	14
Certified /notified	8	0	1	9
Prototypes	0	4	1	5

In a world where energy is becoming the new gold and climate change is a vital issue, any way for consumers to generate their own power is valuable for the savings in money and CO_2 emissions it can bring, and as a way to connect people with the energy they use. We need to monitor the life-cycle economics of urban wind turbines as designs evolve and energy prices change. Governments and regulators must introduce suitable planning guidelines for urban wind, were Denmark has introduced initial initiatives.

The Danish legislation requires type approval for small wind turbines (SWTs). In general, turbines with a swept rotor area below 200 m^2 (16 m diameter) must meet the design requirements of IEC 61400–2, but those below 40 m^2 (7 m diameter) are subject to simpler rules, and below 5 m^2 (2.5 m diameter) a notification to the Danish Energy Agency is all that is required. As Table 3 implies, the market for "turbines" is growing fast: the number of designs certified or notified has tripled in a year, and according to the number of prototypes now entering the process this trend is set to continue.

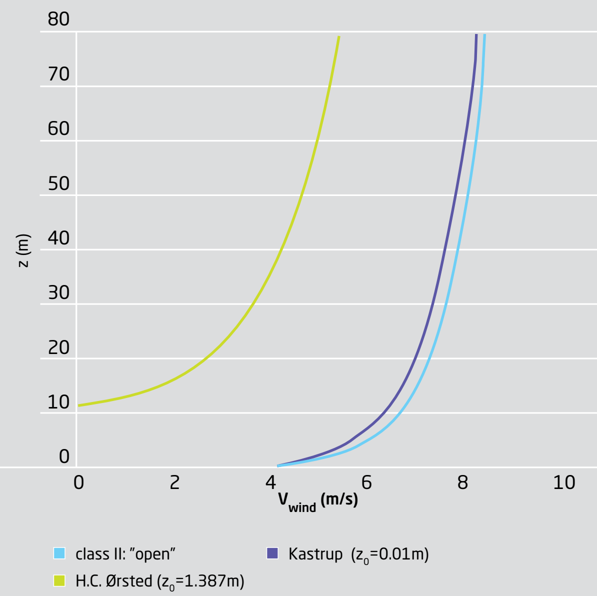
Status of technology

There are many challenges in integrating wind energy into the residential environment. The first is to be clear what we can expect a small wind turbine to produce: even in ideal conditions, the physical size of the rotor sets a firm limit on energy production, and the presence of buildings will generally make matters worse.

Figure 20 shows how wind speed varies with height above the ground for various locations with the same wind climate but different values of local roughness. Even 80 m above the ground, wind speeds in built-up areas are much lower than on open sites. Below a notional height equivalent to about two-thirds the height of the surrounding buildings, the urban wind speed is zero.

Figure 20

How wind velocity profile varies with roughness for the wind climate around Copenhagen. At Kastrup airport (dark blue line), 10 km south of the city centre, the velocity at a given height is much higher than that measured on the rooftop of the H. C. Ørsted Institute near the city centre (green line). The Class II profile commonly used for planning large wind farms matches the Kastrup measurements closely, but is of no use in the urban environment.



It is important to note that a wind profile of this kind follows a semi-empirical logarithmic law that is only strictly valid as an average over large areas. It does not describe the wind micro-climate around an individual turbine, and especially not a turbine mounted on the roof of a city building. For more accurate predictions in specific locations we need to zoom in closer.

Recent work on the airflow around urban buildings has used computational fluid dynamics (CFD) computer simulations based on the city district categorization defined in a previous work. (Badde & Plate, 1994)[64]. Figure 21 shows contours of energy content per square metre at a height corresponding to 60% of the mean building height.

This small-scale variability is matched by the number of ingenious ideas to harvest urban wind. Architects, for example, have clever ways of exploiting pressure differences to provide cooling breezes without the need for electric power[65]. In Tokyo, wind close to buildings and at low heights is harvested with drag-driven vertical-axis turbines and used together with solar energy to run street lamps. In urban areas where more power is needed, lift-driven vertical axis wind turbines (VAWTs) may be appropriate.

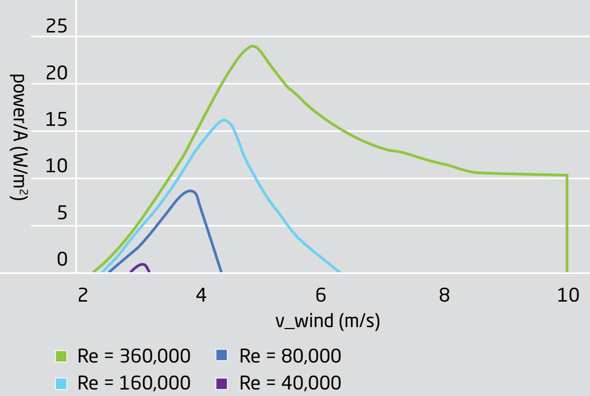
A study of small lift-driven VAWT designs found that they are very different from large turbines in terms of the flow regime around the blades. The comparatively short, narrow blades of small turbines mean that the viscosity of the air

Figure 21

The annual energy content per square metre at 60% of the mean building height. The red contour indicates an annual energy content of 100 kWh/m²/year.

Figure 22

Influence of Reynolds number on power output for a Darrieus VAWT at constant rotational speed (180 rpm) and a constant chord length (blade width). The curves show with blades larger and moving faster, larger wind turbines (with higher Reynolds numbers) capture more energy per unit area than small turbines do.



becomes significant: in engineering terms, Reynolds numbers[66] for small turbines are low, and this has a big influence on performance.

In general, Reynolds numbers should be as high as possible. A VAWT with a radius of 0.83 m has a swept area of around 1.7 m^2 and a Reynolds number close to 80,000. Figure 22 shows that such a turbine would generate a peak power of 15 W (corresponding to a power coefficient CP = 0.23) at a wind speed of about 4 m/s. If the wind were to blow constantly at 4 m/s, this design would produce 131 kWh/y, or just 6% of the average electricity consumption of two people living in an apartment (2,100 kWh/y) – and that ignores losses in the generator, inverter and transformer.

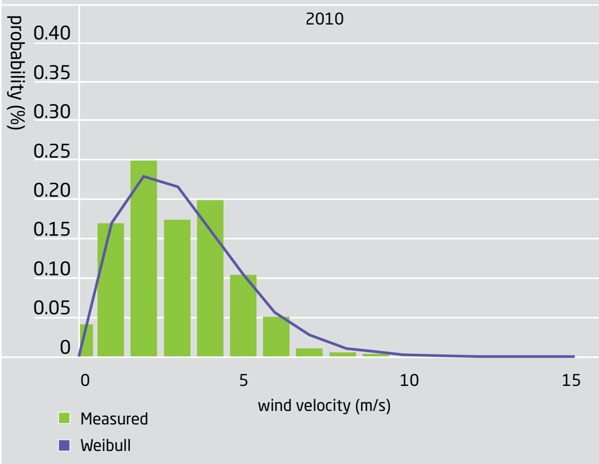
Case study: Copenhagen

Over the last year a Copenhagen company has been importing a particular model of 1 kW VAWT to Denmark. To test its performance the company installed turbines at several locations in the city, took wind measurements at rooftop level and measured the actual energy produced. Figure 23 shows two of the sites, which were chosen to reflect different local topographies.

Wind velocities measured at one of the sites during February and March 2010 was plotted as probability curves (Figure 24) and then integrated using the power curve figures given by the manufacturer. Assuming that seasonal variability is low and that the wind climate recorded for these

Figure 24

Wind measurements for February and March 2010. It was not possible to measure the wind speed at exactly the same position as the turbines, and given the complex topography of the site this could account for some of the difference between the calculated and measured figures. A more probable explanation, however, is that the power curve supplied by the manufacturer is simply wrong.



Total WEIBULL coefficients	k = 1.8 c = 3.5 m/s
Rated power	1.0 kW
Swept area	3.6 m^2
Annual energy production (AEP)	352.864 kWh/a
Load factor	0.04
AEP per m^2	97.75 kWh/a/m^2
Annual wind potential per m^2	265.069 kWh/a/m^2
Cp_average	0.37
V_average	2.9 m/s

Figure 23

Case study in Copenhagen: a Danish company has installed and tested one model of imported 1 kW VAWT at a number of sites in the city. Energy production results were disappointing.

two months is representative of the rest of the year, the calculated annual energy production (AEP) was 350 kWh. The measured energy production, however, was significantly lower.

Even the calculated AEP of 350 kWh is not impressive. A figure often used to describe wind turbines is the load factor (capacity factor): the ratio of the energy actually produced in a given time compared to what would have been produced if the turbine had maintained its full rated output. For large offshore turbines the load factor is generally 30–40%. The load factor for the 1 kW VAWT is only 4%, even based on the manufacturer's exaggerated power curve.

A possible conclusion is that the generator is oversized for the wind conditions. The turbine is rated for full output at a wind velocity of 12 m/s – too high for a wind climate that rarely sees 9 m/s. Fitting a smaller generator for the same swept area would allow the use of a cheaper rotor as well as increasing the load factor.

Future potential

The outlook for wind energy in residential areas is promising. In Denmark, recent legislation has made it possible for private citizens to install their own small wind turbines on favourable conditions, and many countries now encourage new buildings to generate a certain amount of their energy from on-site renewable sources, including wind.

Recent years have seen several examples of wind turbines integrated into building structures. With care, the shape or orientation of the building can improve the performance of the turbines by directing or concentrating the wind. One example is the Bahrain World Trade Center (Figure 25), whose two towers funnel the sea breeze into three horizontal-axis wind turbines mounted on bridges between the towers. The 29 m-diameter turbines are designed to cover 11–15% of the building's energy needs[67]. Another example is the Strata tower, a 148-metre residential building in London and first building in the world to incorporate wind turbines within its structure at the top of the building. The three wind turbines with 9 m rotor diameter and rated at 19kW each and are anticipated to provide 8% of the energy use for the common areas of the building although questions about their real efficiency will remain unanswered until the completion of two years of comprehensive wind data analysis[68].

Of course, most buildings are not replaced in 10 or even 20 years, but the adoption of urban wind turbines could slowly change the appearance of our cities. In any case, this new technology should not be added to every rooftop straight away. Urban wind turbines need time to evolve.

Figure 25

The two towers of the Bahrain World Trade Center funnel sea breezes towards three wind turbines mounted between them[69]. The wind turbines are designed by Norwin Wind Turbine Technologies, based in Denmark[70]. Picture source: http://www.bahrainwtc.com/download.htm

Figure 26

The Strata Tower[71] in London. The three wind turbines are incorporated in the tower structure and designed by Norwin Wind Turbine Technologies, based in Denmark.[72]

Solar energy

Jørgen Fenhann and Peter Sommer-Larsen, Risø DTU; Simon Furbo, DTU Civil Engineering

Solar energy is the most abundant energy resource on earth. In a sustainable future – with an ever-increasing demand for energy – mankind will need to utilise this resource better. Solar energy technologies directly convert sunlight into heat, cooling, electrical energy, "solar fuels" and other synthetic substances. This chapter focuses on solar thermal and photovoltaic (PV) technologies, since these can readily be integrated into the urban environment.

Solar thermal heating (and cooling) and photovoltaics (PV) are both modular technologies that can be used in residential, public and commercial buildings, as well as other constructions such highway sound barriers. Centralised solar power or heating stations near cities may connect to the grid or to district heating systems. Solar thermal heating and PV systems are long-lived and have no moving parts. They need no fuel and little maintenance, and do not create emissions in urban areas struggling to attain acceptable air quality.

These advantages mean that cities, in particular, offer opportunities to use high percentages of solar energy in their energy mixes. In New York, it is estimated that two-thirds of all buildings have roof space that can accommodate solar panels. If fully used, these panels could supply half the city's peak electricity demand and 14% of its total electricity consumption[73]. In Denmark it is assumed that 25% of all roof area could be used for solar energy.

Perspectives for solar energy

When energy supply is considered together with all the other elements of comprehensive urban planning, including transport, air quality, economic development, land use, water and wastewater, PV technology emerges as the best choice[74].

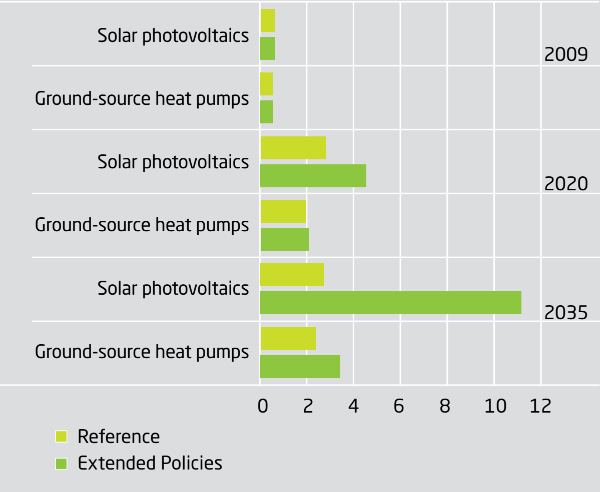
In most regions of the world, a wide variety of solar technologies of varying maturities can contribute to energy services. Solar energy generation represents only a small fraction of total energy consumption today, but markets for solar technologies are growing rapidly. Solar technologies offer a low environmental burden and positive social impacts. Their costs have fallen significantly over the past ten years, and technical advances and supportive public policies continue to promise further reductions. Potential deployment scenarios range from a marginal role for direct solar energy in 2050 to a future in which solar is one of our main sources of energy. The extent to which this happens depends on the degree of continued innovation, cost reductions and supportive public policies[75].

The International Energy Agency (IEA) says that global solar PV capacity has been ramping up at an average annual growth rate of over 40% since 2000, and that by 2050 solar PV will provide 11% of global electricity production[76].

The US Energy Information Administration (EIA) in its Annual Energy Outlook 2011 estimates the influence of federal Investment Tax Credit (ITC) on the predicted residential deployment of PV in the USA. Figure 27: Percentage of single-family homes with PV systems in the USA. In the reference scenario the investment tax credit (ICT) expires by 2016. In the "Extended Policies" scenario it is extended to 2035. Figure 27 captures the essential finding that when the ITC expires in 2016, average growth in solar PV capacity will slow from 39% to less than 1% a year, and a total of 8.9 GW of PV capacity will be installed by 2035. If

Figure 27

Percentage of single-family homes with PV systems in the USA. In the reference scenario the investment tax credit (ICT) expires by 2016. In the "Extended Policies" scenario it is extended to 2035.



the ICT is extended until 2035, PV capacity will grow at 17% a year from 2009 to 2035, and total installed capacity will reach 47.8 GW in 2035, encompassing more than 10% of all homes[77].

For solar to be truly competitive with traditional power sources, the cost and efficiency of turning sunlight into heat, cooling, and electricity need to improve continuously. Few – if any – other renewable energy technologies show such a portfolio of available technical options on different levels of maturity as solar PV. This is one of the premises underlying the expectations that cost reductions will continue over the long term. As a result, we expect solar energy to become one of the key elements in the solution to both our short-term and long-term energy challenges.

Two examples from Denmark illustrate the solar possibilities in cities.

In the town of Marstal on the Danish island of Ærø is a large solar heating plant with 18,000 m^2 of collectors (Figure 28). The plant already provides about one-third of the town's yearly district heating demand, and from 2011 to 2014 it is almost doubling in size, with 15,000 m^2 of new solar collectors plus a 1.5 MW heat pump and a 75,000 m^3

Figure 28

Collector field of Marstal solar district heating plant. Picture: Wikimedia commons.

Figure 29

The positive-energy children's institution in Hørsholm, Greater Copenhagen.
Picture: Adam Mørk Architechtural photography and Christensen & Co. arkitekter a/s.

water storage pit. The enlarged plant is expected to supply more than half of the town's yearly heating demand.

The Marstal project reflects an interesting development in large solar heating plants in Denmark. Since 2006, installed capacity has increased from 30 MWt to 150 MWt – a factor of five in five years. This trend seems to be continuing in 2011: according to the Danish District Heating Association's solar group, more than 100,000 m^2 of solar collectors will be installed in 2011.

The main reason for this dramatic development is that it is good business. Even without subsidies, solar heat is now competitive with other fuels, thanks to falling prices and increased efficiency for solar systems on the one hand, and on the other rising prices for other fuels. The main barriers to large solar heating plants in cities are lack of space for the collectors and lack of experience in district heating.

In the municipality of Hørsholm in the northern part of Greater Copenhagen, a 1,300 m^2 integrated institution for 100 children was inaugurated in May 2011 (Figure 29). The building is a CO_2-neutral "active house" which meets Denmark's Class 1 standard for energy. It has 250 m^2 of solar PV, 50 m^2 of solar panels for heating, and 1,000 m of buried pipes that allow heat pumps to recover stored solar heat when the sun is not shining. Solar PV electricity drives the heat pumps and the underfloor heating system.

There are no other heat sources except for passive heating from the façade windows and the 80 roof windows with their double and triple glazing. Low-energy lighting and the most efficient appliances keep electricity consumption low. On a yearly basis the house produce more energy than it uses, so excess electricity is sold to the grid. Ventilation, temperature and light levels are controlled automatically, producing optimal conditions for the children and the 30-strong staff. An additional benefit is the low level of noise. The children growing up in such an environment see at first hand how effective solar energy can be in the urban environment.

Technology status

A review of solar electric technologies can be found in the previous Risø Energy Report[78]. With respect to PV, 2010 saw a dramatic increase in installations and a dramatic price reduction. Globally more than 18 GW of PV systems were installed in 2010, nearly doubling the total global installed capacity, which now stands at 39 GW. At the same time the price of PV systems has continued to decrease and in many countries, including Denmark, householders can now get electricity from PV systems at lower cost than from utility companies.

Strictly defined, building-integrated PV (BIPV) replaces conventional building materials with solar cells in parts of the building envelope. In a wider definition, solar cell modules incorporated into the construction of new buildings or retrofitted to old buildings are also considered BIPV. Rooftop-mounted panels generally do not count as BIPV unless they also constitute an architectural element.

Two-thirds of global installed PV capacity takes the form of grid-connected distributed systems. Such systems may be on or integrated into the customer's premises, often on the demand side of the electricity meter; on public and commercial buildings; or elsewhere in the built environment, for instance on motorway sound barriers.

The IEA's Photovoltaic Power Systems Programme (IEA-PVPS) sub-task 10 considers urban-scale PV applications[79]. PV can provide many solutions for cities, it says, because:

- with half the world's population living in high-density urban areas, cities represent a major PV market;
- cities can deploy PV rapidly because they have the jurisdiction to remove obstacles; and
- urban PV deployment has the potential to modify the appearance of the built environment by integrating functional energy solutions and aesthetics.

The sub-task concludes by pointing to the need to integrate urban energy with cities' other long-term plans: "...When energy is integrated with all the other elements of comprehensive planning – including transport, air quality, economic development, land use, water and wastewater – PV technology emerges as the best option".

The IEA sub-task has published several reports and a book[80], Photovoltaics in the Urban Environment. One important issue is how the grid will react if PV systems are widely rolled out in urban areas. Potential problems include overvoltage and undervoltage, instantaneous voltage change, harmonics and unintended islanding. The sub-task published a separate report on this issue in 2009[81]; the key conclusion is that: "…most of the potential problems studied have yet to become tangible problems at the present time. Furthermore, even the issues with the potential to become problems in the future are generally not serious issues, and can either be dealt with sufficiently with existing technologies or else avoided with proper planning and design."

Inverters are a key part of PV systems, not least because they can remedy some of the potential problems listed above. Modern inverters allow grid suppliers to communicate with them and control their output power.

Figure 30

Dezhou is "China Solar City", a "model city for the use of renewable energy in building".
Picture: http://www.himin.com/english/News/UploadFiles_8962/201008/2010081219315283.jpg

The IEA in general has also adopted the concept of "solar cities" which focus on solar energy. Some examples are:

In the USA[82] solar cities include Ann Arbor (MI), Austin (TX), Berkeley (CA), Boston (MA), Denver (CO), Houston (TX), Knoxville (TN), Madison (WI), Milwaukee (WI), Minneapolis-Saint Paul (MN), New Orleans (LA), New York City (NY), Orlando (FL), Philadelphia (PA), Pittsburgh (PA), Portland (OR), Sacramento (CA), Salt Lake City (UT), San Antonio (TX), San Diego (CA), San Francisco (CA), San José (CA), Santa Rosa (CA), Seattle (WA) and Tucson (AZ).

Australia's solar cities[83] include Adelaide, Alice Springs, Blacktown, Central Victoria, Moreland, Perth and Townsville.

In the UAE, Masdar City is an emerging global hub for renewable energy (see also chapter 4). Solar solutions include a 10 MW PV plant that produces 18,000 MWh/y of electricity and a parabolic trough collector system to drive air conditioning. The roof of the Masdar Headquarters building will produce 5.5 GWh of electricity annually.

At the centre of China Solar Valley in Dezhou, Shandong province, is the Sun-Moon Mansion, the headquarters of Himin Solar Energy (Figure 30). The company was founded in 1995 by Ming Huang, an oil equipment engineer concerned about dependence on fossil fuels. Now Himin is the world's largest make of solar water heaters, and Solar Valley is the world's largest solar park. As of 2009, Sun-Moon Mansion was the largest solar structure in the world. It provided the main conference hall for the Fourth International Solar Cities Conference in 2010. The building covers an area of 750,000 m^2 and provides space for displays, R&D, work, meetings, education, a hotel and recreational facilities. It uses solar technologies for hot water, heating, cooling and power generation.

Dezhou itself is "China Solar City", a "model city for the use of renewable energy in building". Dezhou's local government is dedicated to the use of solar energy and the promotion of the solar industry. Visitors notice the large number of solar collectors on the roofs of the town, which also uses PV arrays to power more than 30 km of street lights and many of the traffic lights.

Future developments

Current simple financial payback times for solar heating systems in Denmark are 5–15 years, depending on the type of system and the timing of the installation. In other countries simple financial payback times can be higher or lower, depending on energy costs, the design of the system and the solar radiation potential. It is estimated that technological improvements can halve these payback times.

R&D in small solar heating systems should concentrate on hot water tanks and the interplay between solar collectors and other renewable energy sources. The development of larger systems should concentrate on solar collectors and seasonal heat storage.

Bioenergy

Kim Pilegaard and Leif Sønderberg Petersen, Risø DTU

Waste-to-energy (WTE)

Municipal solid waste (MSW) is waste from households and commercial activities discarded in urban areas. MSW consists of everyday items such as food waste, paper, product packaging and clothing. The organic components of MSW and other organic waste streams are thus sources of biomass that can be converted to energy within smart cities. Today the waste-to-energy (WTE) industry is mature, with proven technologies to produce electricity and heat or cooling through incineration. Many communities are also starting to look at newer WTE technologies like gasification and ethanol production for transport fuel (Figure 31).

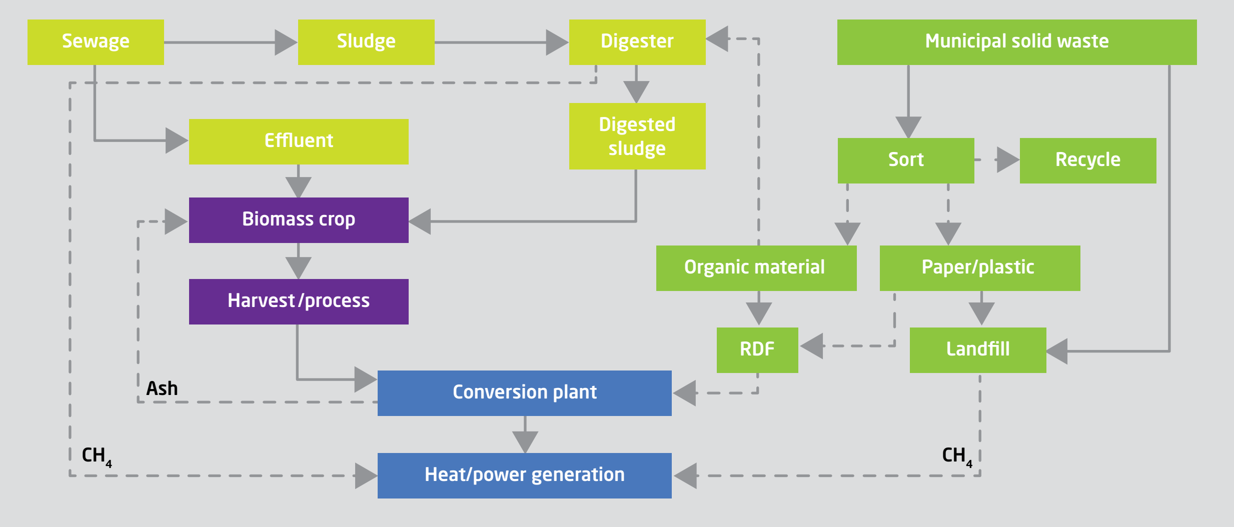
Several factors have contributed to the renewed interest in MSW technologies. First of all, many local landfills are at capacity and about to close, and there is public resistance to new disposal sites. Second, tipping fees are expected to rise in many locations, and as fuel prices rise, the cost of transporting MSW to distant landfills will do likewise[84].

At the same time public policies are spurring the development of MSW technologies. The EU waste hierarchy ((a) prevention; (b) preparation for re-use; (c) recycling; (d) other recovery, e.g. energy recovery; and (e) disposal)[85] aims to extract the maximum practical benefits from products and to generate the minimum amount of waste. In Denmark a recent reorganisation of waste incineration will ensure that the energy from waste is used even better. Recovery of energy from waste also contributes positively to the Danish government's goal of more sustainable energy[86].

Combustion and incineration

Urban organic waste arising from food processing, food waste, sewage, packaging, paper and textiles typically reaches around 1 t/person/y in OECD countries[88].

Figure 31
Urban sewage treatment and MSW can both yield energy, while nutrients from sewage can be recycled to grow energy crops.[87]



It is estimated that about 130 million tonnes of MSW are combusted annually in over 600 WTE facilities worldwide, producing electricity and steam for district heating and recovered metals for recycling[89].

In Denmark, the company Amagerforbrænding produces electricity and energy for district heating by incinerating waste from five municipalities around the capital (Dragør, Frederiksberg, Hvidovre, Copenhagen and Tårnby). In 2010 the company burned 404,000 t of waste in four furnaces[90]. The waste consists of:

- refuse collected from private households (50%);
- incinerable waste from the recycling stations (10%); and
- industrial waste (40%).

The energy from Amagerforbrænding's incinerators supplies 140,000 households with either electricity or district heating.

Gasification
MSW can be gasified to produce syngas, which consists mainly of hydrogen, carbon monoxide and carbon dioxide. The energy value is approximately half that of natural gas. After cleaning, the gas can be burned to produce heat and power, or after further processing it can be turned into other chemicals and liquid fuels.

Gasification is a future alternative to waste incineration for the thermal treatment of MSW. The gasification process offers good scope for energy recovery and reduces emissions of potential pollutants[91].

Combined gasification and fermentation
In the USA the first facility to produce both ethanol and electricity from waste will begin production in 2012. The Indian River BioEnergy Centre in Florida will produce 8 million gallons of bioethanol each year and 6 MW of power from local waste. The conversion process combines gasification and fermentation. Organic waste reacts with oxygen to produce syngas that is fed to naturally occurring bacteria. The bacteria convert the syngas to ethanol, which is then purified for use as transport fuel[92].

Plasma arc technology
In the plasma arc process, waste is heated by a plasma torch to produce syngas. The US company Geoplasma has been commissioned by St. Lucie County, Florida, to build a plasma arc plant that will process 600 t/day of MSW and up to 62 t/day of tyres. It will generate 19 MW of electricity to power more than 20,000 homes[93].

Anaerobic digestion
Many cities already produce biogas through anaerobic digestion of sewage effluent and sludge as well as other organic feedstocks from farming and food processing plants[94]. The organic fraction of municipal solid waste

(OFMSW) and organics-rich industrial wastewater can also be used. The resulting biogas can be distributed via local gas grids, used as a transport fuel or converted to electricity by gas engines or micro-CHP plants.

Landfill gas capture

Landfill gas can be used directly on site, either by burning to produce heat or as fuel for gas engines to generate power. The gas must be scrubbed to remove impurities before it can be used in an engine or injected into a gas pipeline.

Besides providing a source of renewable energy, capturing landfill gas also reduces greenhouse gases. Methane is a much more potent greenhouse gas than CO_2, so burning it has a net positive effect on emissions.

Landfill gas used to be seen as a problem, but recent advances in our knowledge of landfill behaviour and the decomposition of MSW have created interest in maximising the amount of gas that can be extracted from landfills. Many countries are now essentially operating landfills as bioreactors to produce more gas and to stabilise the resulting waste more quickly[95].

In 2008 the city of Vaasa in Finland hosted a visionary housing exhibition on the theme of sustainable energy for buildings. Vaasa has an old landfill, and from this came the idea of using landfill gas to supply electricity and heat to the houses and apartments in the exhibition. Finnish engine manufacturer Wärtsilä built a 20 kW_e power plant based on SOFC fuel cell stacks from Topsoe Fuel Cell (Figure 32). With a heat output of 14–17 kW the unit can supply up to ten households.

The fuel cell power plant in Vaasa has run for more than 2,000 hours on landfill gas, with very positive results. The unit was dismantled, inspected and returned to service in autumn 2010. It then ran for a further 5,000 hours before the next inspection in the first quarter of 2011[96].

Biomass-fuelled small-scale CHP

Small-scale CHP units based on Stirling engines (Figure 33) convert solid biomass to electricity and heat very efficiently. They can be used in large urban buildings wherever a supply of biomass, such as wood chips, is available within easy reach. Read more about Stirling engines later in this chapter.

Algal biomass

An innovative way to produce biomass in future cities could be to convert flat rooftops into facilities for growing blue-green algae (cyanobacteria). At the right temperature and with the right nutrients algae can grow far more rapidly than other forms of biomass, so they could be continually cropped to produce biofuels or to run small CHP plants. Roofs could be designed to harvest water, collect solar energy and grow algal biomass at the same time[97].

Figure 32

Wärtsilä 20 kW SOFC fuel cell power plant using gas from an old landfill to provide sustainable electricity and heat in the Finnish city of Vaasa. Picture: Wärtsilä.

Figure 33

35 kWe SD4-E bio-fuelled Stirling engine manufactured by Stirling.dk. Picture: Stirling.dk

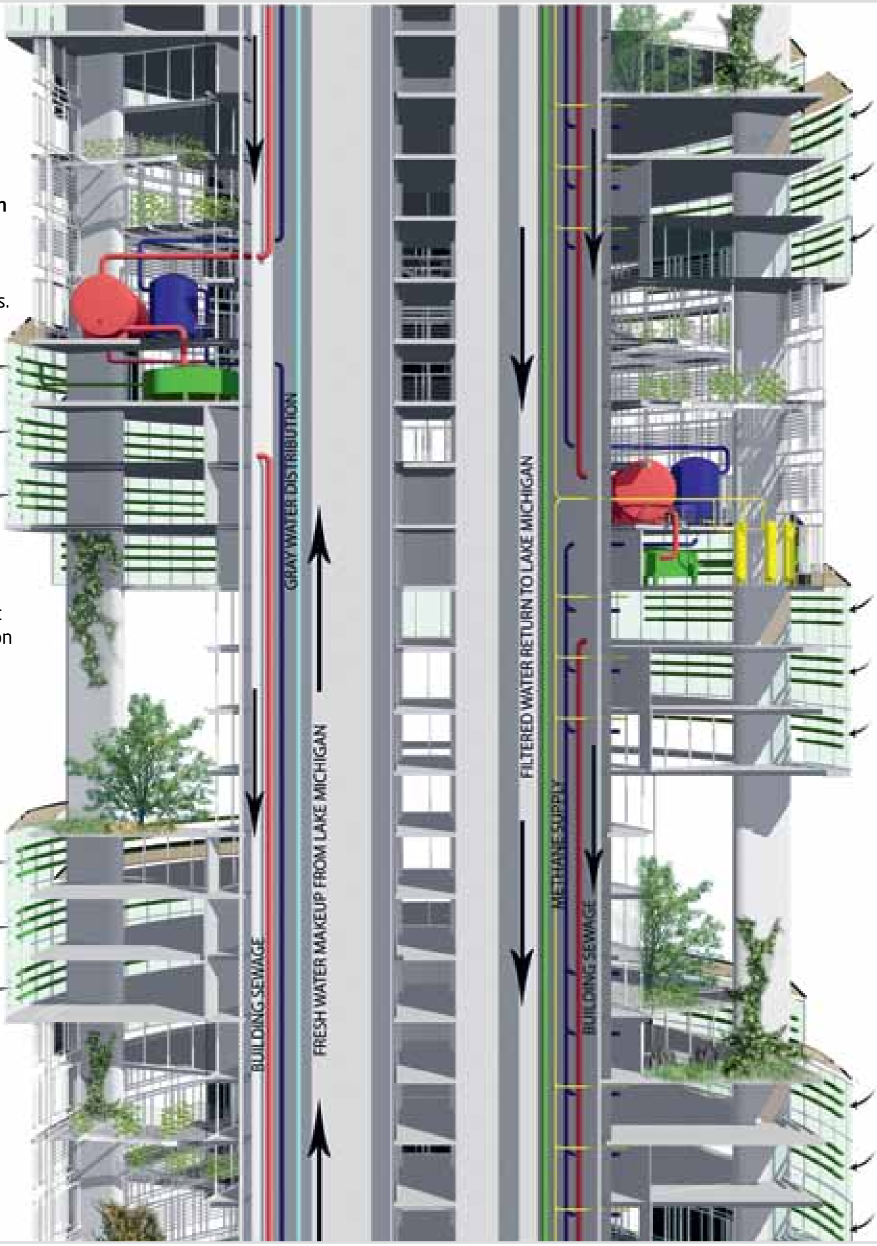
Biodiesel can also be produced from microalgae grown in sewage treatment plants, taking up nutrients from the wastewater and so helping the water purification process[98].

Urban agriculture

According to the UN Food and Agriculture Organization (FAO), "urban agriculture" describes the production of crops and livestock within cities and towns and their surrounding areas. Urban agriculture can involve anything

Figure 34

Vertical farming, design by Blake Kurasek. Illustration by Blake Kurasek.



from small vegetable gardens in back yards to farming of community land by associations or neighbourhood groups. It is commonly practised on fallow public and private spaces, wetlands and underdeveloped areas; rarely is it found on land specifically designated for agriculture.

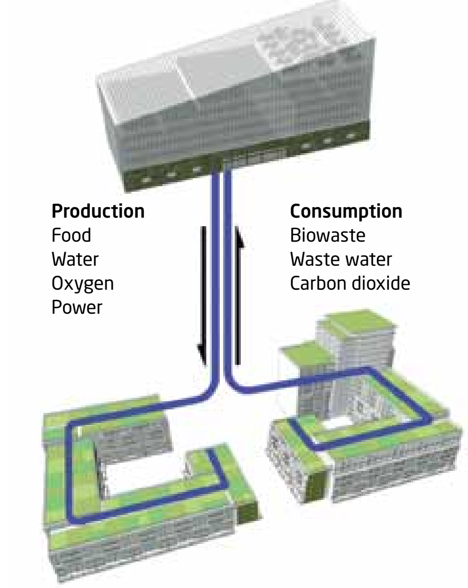
In many countries urban agriculture is informal and sometimes even illegal. Competition for land is a frequent source of conflict. Other contentious issues include the environmental impact of urban agriculture and food safety concerns, particularly relating to livestock production. While data are scarce, urban agriculture is an important reality in many developing countries. Up to 70% of urban households participate in agricultural activities, according to the first systematic quantification of urban agriculture conducted by the FAO. The study is based on data from 15 developing and transition countries for which comparable statistics are available[99].

Urban agriculture seems particularly important in low-income countries. But even in more developed economies, a significant proportion of urban households are involved in farming.

With few exceptions, poor urban dwellers are more likely to participate in crop and livestock production than richer households. In many countries more than half of all urban households in the poorest expenditure quintile rely in part on their own agricultural activities to satisfy their food needs.

Figure 35

Vertical farm design showing the flow of materials.[101]



Urban agriculture has been made smarter through the development of new concepts like "vertical farming", a greenhouse-inspired concept that scales up a niche technology (Figure 34, Figure 35)[100]. Another example is AeroFarms, a company based in Ithaca, NY, USA that has developed an indoor, soil-less system of urban agriculture. By growing leafy greens in a cloth medium under LED lights, the technique eliminates the need for sunlight and pesticides, and dramatically reduces water consumption (see also De Groenten uit Amsterdam in chapter 5.

These concepts make farming smart and distributed, in the same way that energy is becoming smart and distributed. That paves the way for urban farming as a key concept in smart cities. Urban farming can rely on the availability of organic waste, heat and electricity produced within the city. The distances over which the food will need to be transported are small, and the food will be fresher and healthier since it will not need to spend days or weeks in transit.

Heat pumps

Brian Elmegaard, DTU Mechanical Engineering

A heat pump supplies heat at the required temperature by taking energy from two inputs: a low-temperature heat source and a source of driving energy, which may be mechanical power or high-temperature heat. It is therefore a way to use low-temperature heat, for instance waste heat from industry or solar heat absorbed by the ground, for heating duties that require a higher temperature. There are two main types of heat pumps: mechanical and thermal. Heat pumps are rated according to a figure called the coefficient of performance (COP), which is the ratio of heat produced to electricity (or high-temperature heat) consumed.

The emissions from any heat pump are determined by the source of the energy used to drive it. If this energy comes from a renewable source such as wind power, solar power, solar heating, waste heat or geothermal energy, the heat pump will not give rise to any greenhouse gas emissions on its own account. Currently this is only rarely the case, so heat pumps in this respect may not perform better than other heating technologies.

Future megacities may be able to make good use of heat pumps because their dense populations may reveal significant potential for optimising heat supplies[102]. By minimising exergy losses, this will give the best possible utilisation of energy sources, whether renewable or not. Innovative solutions integrating power, heat and cooling through the use of alternative media have been presented recently[103].

Mechanically driven heat pumps

A mechanically driven heat pump is essentially a conventional refrigeration plant. It operates according to the Rankine thermodynamic cycle: a compressor generates a pressure difference that is used to extract energy at low temperature and supply it at a higher temperature.

The COP of a mechanically driven heat pump used for space heating is in the range 2.6–4.6; ground-source installations, which get their low-temperature heat from buried pipes, generally perform better than air-source systems, which take heat from the atmosphere[104].

Heat pumps are a generally mature technology and are widely used to heat residential buildings, but there are significant opportunities to improve their performance[105,106]. Ref.[] gives a general review of recent developments in heat pump technology. While conventional heat pump working fluids are HFCs and HCFCs, which can act as greenhouse gases and also damage the earth's ozone layer, much research is now taking place into alternative refrigerants such as ammonia (R717), carbon dioxide (R744), hydrocarbons and even water. In industrial installations heat pumps are not yet a state-of-the-art technology, but significant efforts are being made to make them competitive with other methods of heat supply.

Thermally driven heat pumps

Thermally driven heat pumps use the same thermodynamic cycle as their mechanical counterparts. However, they generate the required pressure difference by using high-temperature heat to influence the equilibrium that controls the pressure, temperature, and concentration of a mixture of chemical substances.

Thermally driven heat pumps come in various types. In absorption heat pumps it is common to use a solution of lithium bromide (LiBr) in water as the "working pair", but other mixtures are under consideration[108]. For solid-state adsorption systems several mixtures are under development[109].

The COP of a thermally driven heat pump is typically around 2, depending on the temperatures used. The exergetic efficiency is in the same range as for a mechanical system.

Micro-CHP

Anders Smith, Risø DTU; Nigel Brandon, Imperial College, UK; Henrik Carlsen, DTU Mechanical Engineering; Søren Linderoth, Risø DTU

Principles of micro-CHP

Combined heat and power (CHP), also known as cogeneration, is the simultaneous generation of thermal energy and electrical energy in a single unit. Large-scale CHP is a mature technology used in many countries, in particular in north-western Europe, where the electricity is delivered to the central grid while the heat is distributed through district heating networks. Such power plants typically have an installed capacity of from one to several MW_e.

However, CHP on a much smaller scale may be attractive in increasing the flexibility of the energy system. The EU defines micro-CHP units as those with a maximum electrical capacity below 50 kW_e[110], but much of the development effort is directed towards small units for individual households with capacities down to as little as 1 kW_e. Their fuel is most often natural gas, but other fuels may be attractive in remote locations.

Although 1 kW_e is sufficient to cover the average power consumption of a typical household, peak demand may be several times larger. The household will therefore still need to be grid-connected, and this has the added advantage that surplus power may be exported to the grid.

Heat demand depends very much on geographical location, season and the state of the thermal envelope of the building. In climates with moderately cold winters heat demand may easily exceed power demand by a factor of three or four. Since adding power capacity is more expensive than adding heat capacity, it is important to dimension the unit correctly, especially its power-to-heat ratio[111]. This can for instance be done by adding an auxiliary burner.

Conversely, a high power-to-heat ratio will be attractive for use in modern low-energy housing with its modest heating demands. In tropical and subtropical climates where heat demand is low, the generated heat may alternatively be used to drive an absorption cooling cycle for refrigeration or air conditioning[112]. Such a system for polygeneration or trigeneration is sometimes called CCHP (combined cooling, heating and power).

Widespread use of micro-CHP will increase the flexibility of the total energy system by adding a large number of individual generating units with the ability to up-regulate and down-regulate rapidly. This will make it easier to

Table 4
Technologies for micro-CHP.

Technology	Fuel cells		Internal combustion			External combustion	
	SOFC	PEMFC	Gas engine	Diesel engine	Micro-turbine	Stirling engine	Organic Rankine cycle
Primary fuel	Natural gas	Hydrogen	Natural gas	Diesel	Natural gas	any	any
Maximum electrical efficiency	35-60%	40-50%	22-26%	34%	25-35%	12-26%	10%
Total efficiency (electricity + heat)	>90%	>90%	>90%	>90%	>80%	>80%	90%
Technology status	Demonstration	Commercial entry	Commercial	Commercial	R&D	Commercial	R&D

accommodate increasing amounts of fluctuating power sources such as wind turbines in the energy system. When micro-CHP displaces power generation in coal-fired power plants this significantly reduces greenhouse gas emissions. To take full advantage of such a system requires a smart grid that allows net metering and variable pricing. There are also fundamental questions to be addressed such as whether the individual generating capacity should be put at the disposal of the grid system operator[113].

From the systems viewpoint, micro-CHP may increase the efficiency of the energy system because local generation of power and heat avoids transmission losses. These losses are currently on the order of 5–7% for electricity distribution and 20% for district heating, so eliminating them might more than offset the lower generating efficiency of small units compared to central power plants. Micro-CHP may also have significantly better part-load characteristics than large power plants.

For end-users, micro-CHP systems are still significantly more expensive than traditional boilers. This makes market entry sensitive to factors such as favourable legislation and tariffs.

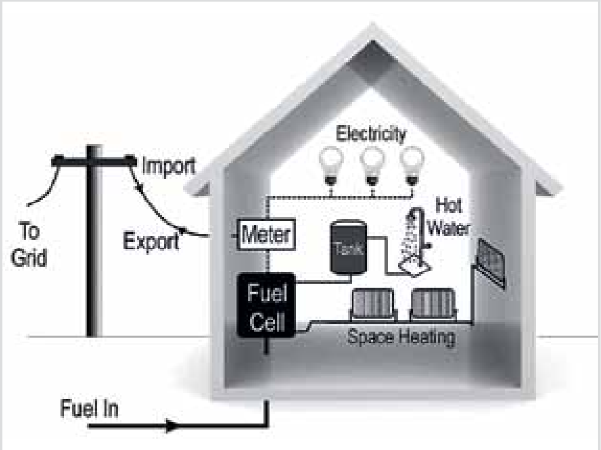
Fuel cells

Fuel cells are electrochemical cells which convert the chemical energy of a fuel directly into electricity, generating heat in the process. The direct conversion makes for high electrical efficiency – up to 60% for certain types of fuel cell – and thus a relatively high power-to-heat ratio. In addition to the fuel cell stacks themselves (each consisting of 50–100 individual cells electrically connected in series and manifolded for fuel and air distribution), a complete micro-CHP unit consists of several auxiliary components, including a reformer for fuel treatment, possibly combined with removal of impurities such as sulphur, an afterburner to combust unused fuel, and an inverter to allow the DC output of the fuel cell stack to be converted to AC and connected to the grid. An auxiliary burner to increase heat output and a heat store are often added.

There are several different kinds of fuel cells, each with specific fuel requirements and operating temperature. Two types in particular are considered promising for micro-CHP: solid oxide fuel cells (SOFCs) and polymer electrolyte membrane fuel cells (PEMFCs)[114].

Figure 36

Micro-CHP based on a fuel cell, showing import and export of electricity.



Micro-CHP based on SOFCs offers the highest electrical efficiency of any micro-CHP technology on a wide range of fuels, including natural gas. As such it has the highest power-to-heat ratio, allowing operation for the widest period of time. This is economically advantageous in many parts of the world where regulations do not permit heat to be dumped from a micro-CHP unit, so that units must be sized for the minimum heat requirement. The technology is at the level of field trials in private homes, but commercial units are not yet available. The critical outstanding question is the service life of the units.

PEMFC-based micro-CHP offers the highest electrical efficiency when operating on pure hydrogen. Other fuels can be utilized if they are reformed to generate hydrogen. PEMFCs are less efficient than equivalent SOFC systems on carbon-containing fuels such as natural gas or biogas. Commercially available PEMFC micro-CHP units exist, operating at 80–100°C. Here the main challenge is cost. To increase efficiency and reduce cost, some developers are also pursuing higher temperature (around 150–180°C) PEMFC micro-CHP, but this technology is far less mature.

Fuel cells, in particular SOFCs, can be designed for reversible operation: they can generate power from fuel, or use power to produce hydrogen (and oxygen) through the electrolysis of water. This could increase the flexibility of the energy system, for instance by allowing surplus wind power to be stored as hydrogen in the natural gas grid. Such systems, however, have only been tested at the lab scale so far.

Combustion engines

Internal combustion engines
Ordinary internal combustion engines (ICEs) are a well-proven technology, known from automobile and ship propulsion for more than 100 years. ICE-based micro-CHP systems with an electric power output below 5 kW_e have only been commercially available for around ten years, but today they too are a proven technology.

An ICE micro-CHP system consists of either a spark-ignition gas engine or a diesel engine connected directly to an AC generator. The generator is connected directly to the grid, as there is no need for an inverter. Waste heat from the engine's cooling system is transferred to the hot water system in the building, along with further heat extracted from the exhaust by a heat exchanger (economiser). A control system monitors the operation and the power and heat production.

The most common type of engine for ICE micro-CHP is a small single-cylinder spark ignition engine using natural gas as fuel (units using biogas are also available). Electric power output for the smallest units is 1 kW_e, though most manufacturers target the range 5–50 kW_e. Natural gas units normally use catalytic converters to reduce emissions, but this is not possible when burning biogas, since this contains contaminants such as microparticles and sulphur which destroy the catalyst.

Gas engine micro-CHP units have moderate electric efficiency (22–26%). Micro-CHP units based on small diesel engines offer somewhat higher electrical efficiency (up to 34%); such units have also been commercially available for some years.

The main advantages of ICE-based micro-CHP are the simple and proven technology, fuel flexibility, and relatively low cost. The main disadvantages are the moderate electrical efficiency, expensive servicing (including overhaul, oil consumption and spark plugs), emissions, and challenges in developing systems small enough for domestic use (below 5 kW_e).

Stirling engines

Another technology suited to micro-CHP is the Stirling engine[115]. The main difference between a Stirling engine and an ICE is that in the former combustion takes place not inside the cylinder but outside, as in an ordinary boiler. The engine is driven by a working fluid performing a closed thermodynamic cycle; heat from the combustion of the fuel is transferred to the working fluid by passing the hot exhaust through a heat exchanger, while another heat exchanger transfers waste heat from the cycle to the cooling water. Any heat source can be used and the Stirling engine is therefore very fuel-flexible.

As the Stirling engine is based on a closed cycle, any working gas can be used. Helium is the normal choice but hydrogen, nitrogen and air are also used. Small Stirling units can be designed as "free-piston" engines in which the pistons are moved by gas pressure and controlled by springs and gas dampers. With no need for a crankshaft or other rotating parts, the life of the mechanical components is nearly infinite, and noise levels low. An AC linear generator is connected directly to the working piston, resulting in a simple and reliable design.

The temperature of the hot heat exchanger is normally 500-700°C which means that the temperature of the exhaust gas after passing through the hot heat exchanger will still be as high as 550-750°C. To increase efficiency, some of this waste heat can be used to preheat the combustion air, though the resulting higher combustion temperature risks the formation of thermal NO_x.

The generator is typically connected directly to the grid. As with ICEs, waste heat from the engine cooling is transferred to the hot water system in the building. This is also done with the waste heat from the exhaust using an economiser. A control monitors the combustion and the operation, power output and heat production.

Several micro-CHP units based on Stirling engines have been released to the market, and the technology is approaching maturity. Electrical efficiency is typically 10–12% for units without air preheaters, and up to 26% with preheaters.

The advantages of Stirling engine micro-CHP systems are their simple design and low servicing needs, fuel flexibility, long lifetime, low noise, and emissions comparable to a conventional boiler. Systems are easy to design for power outputs down to 1 kW_e or below, and costs could be low once the units are manufactured on a large scale. The disadvantages are the modest electric efficiency and the fact that the technology has only recently entered the market.

Micro-turbines

A number of R&D projects have tried to develop small-scale gas turbines ("micro-turbines") for small CHP units, but so far very few have succeeded. A micro-turbine consists of a compressor, a combustion chamber and a turbine. Small micro-turbines often also include a recuperator to preheat the compressed air before the combustion chamber using heat from the hot turbine exhaust. The turbine is connected directly to a high-speed generator, with a frequency converter to deliver 50 Hz (or 60 Hz) power to the grid.

Advantages of micro-turbines include low servicing requirements and low emissions[116]. However, units with power outputs below 30 kW_e are not yet on the market, and in the 10–50 kW_e range competition from ICEs is severe.

Organic Rankine cycle

The organic Rankine cycle (ORC) is a thermodynamic "steam" cycle based on an organic working fluid instead of water. A pump pressurises the working fluid, which then enters a boiler where it evaporates and the resulting vapour is superheated. The vapour then expands through a turbine, generating shaft power in the process, before entering a condenser. A recuperator may be incorporated to increase efficiency. Although there are several ongoing R&D projects in ORC micro-CHP (such as reference 117) it will be some time before practical units reach the market.

Worldwide status and outlook

At present the market penetration of micro-CHP systems is facilitated to a large extent by government subsidies. Japan, for instance, has a long-standing commitment to micro-CHP and a substantial subsidy per unit. This has helped to create a user base of more than 50,000 ICE-based units (mainly Honda ECOWILL gas engines) and several thousand PEMFC-based units. The fuel cell units are developed in collaboration with the Japanese gas utilities. The PEMFC-based ENE FARM unit from Tokyo Gas/Panasonic operates on natural gas and has demonstrated 40,000 hours of operation. However, the present retail price of ¥2,761,500 ($33,000) (excluding installation) must come down, even with the current ¥1,000,000 government subsidy. The Japanese SOFC programme has recently begun field testing units developed by Kyocera.

In the rest of Asia, Korea has a programme for fuel-cell-based micro-CHP with more than 100 PEMFC units being deployed in field trials by the utility KOGAS. Other technologies include a Stirling unit manufactured by KD Navien.

In Europe, Germany is an important market due to its Kräft-Wärme-Kopplungsgesetz ("CHP law"), which sets a feed-in tariff for electricity produced by micro-CHP; in addition various tax reliefs apply. Manufacturers include Vaillant (with Honda gas engines), Senertech Dachs (gas engines), Baxi Innotech (PEMFC) and Hexis (SOFC). The gas engines have sold more than 10,000 units, while the fuel cell units are being field tested within the Callux FC project.

In the UK micro-CHP technologies also benefit from a feed-in tariff. The main players include Baxi and WhisperGen (both Stirling) and Ceres Power (SOFC). The Netherlands is field testing Stirling units from KD Navien and Remeha. In Denmark PEMFC and SOFC units are being field tested in the Danish Micro Combined Heat and Power project. The SOFC technology is supplied by Topsoe Fuel Cell.

In the USA a number of tax credits and incentives are available at both federal and state levels, for example the Self Generation Incentive Program in California. Companies selling micro-CHP include Freewatt (Honda ICE technology), Marathon Engine ecopower (ICE) and the PEMFC-based Plug Power and ClearEdge.

The outlook for micro-CHP thus looks promising, with a number of different technologies at or close to commercialisation. The most mature technologies are the ICE gas engine and the Stirling engine, while PEMFCs need to come down in price before they can be competitive. SOFC-based systems will be ready for commercialisation within a few years if the necessary lifetime can be demonstrated. Other technologies including CCHP and reversible systems are further from the market. Finally it should be emphasised that widespread market penetration of micro-CHP will also support the implementation of smart grids and their associated energy infrastructure.

New customer services

Marie Münster and Frits Møller Andersen, Risø DTU; Maria Josefina Figueroa Meza and Thomas Jensen, DTU Transport;
Morten Hofmeister, Danish Development Centre for District Heating

This chapter focuses on the challenge of motivating energy service customers to make best use of available smart technologies. This can be done through economic incentives, but also through information and education, regulation and reorganisation, and by improving services or customer comfort (Figure 37).

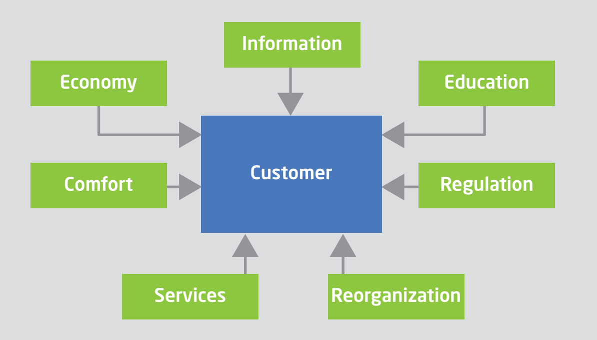
The European Covenant of Mayors initiative[118], where local and regional authorities voluntarily commit to increase energy efficiency and use of renewable energy sources obliges participating cities to set targets and list actions across the built environment, local energy networks and urban transport systems. The following sections provide examples of how energy users can be motivated to participate in making cities smarter. For the built environment the example concerns flexible use of electricity. For local energy networks the example is about efficient use of district heating, and for urban transport systems we discuss service improvements. In each case we describe the current situation and show how new ICT solutions can increase the involvement of customers and improve the sustainability of the service.

Flexible use of electricity

Buildings use energy for controlling the indoor climate and to operate many different electrical appliances. Smart technologies in the built environment can reduce overall energy use, cut bills by using energy when cheapest, improve consumer comfort, and support a sustainable way of living.

Indoor climate is controlled most effectively through the design of buildings at the beginning of their lives; once the building is complete, changes are difficult and expensive.

Figure 37
Ways of motivating customers to use smart technologies.



This section therefore addresses only how to control the times during which appliances operate – an area that can be influenced relatively quickly and easily through modern ICT.

Electrical appliances should ideally operate so as to minimize total consumption and – equally important – use electricity when excess capacity is available and the market price low. Changes in the timing of electricity consumption can save customers money, and can have even bigger benefits for power companies and society by reducing peak loads and avoiding the need for new power lines.

Household customers have a big influence on peak demand. Figure 38 shows that during the peak that occurs on late winter afternoons in Denmark, households account for about half of all the power used.

Opportunities for domestic consumers to change their consumption profiles are limited, and there would be little incentive for them to react to hourly market prices even if they had this information. This is because in Denmark the market price of electricity accounts for only about a quarter of the average domestic bill; the rest covers fixed payments, transmission, public service obligations (PSO) and taxes. Today, although their consumption is metered by the hour, no households have hourly billing.

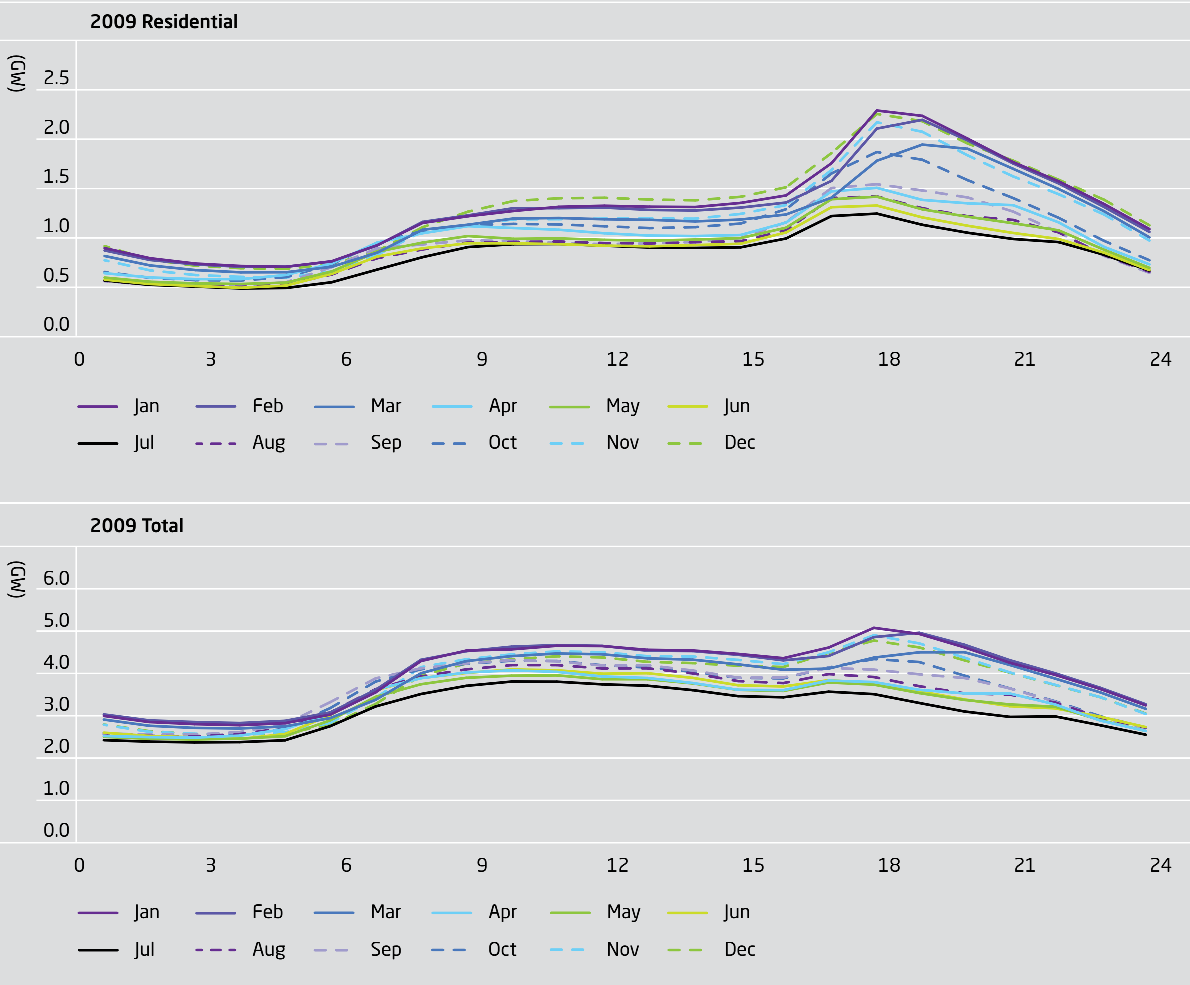
For enterprises, taxes are much lower and so there is more incentive to use electricity when it is cheap. Even so, only about half of all large consumers (those who use more than 100,000 kWh/year) have hourly billing. This is partly due to the large fees charged by the electricity companies for this service. Hourly billing currently costs around DKK 5,000 a year, so a company using 100,000 kWh/y will pay an extra DKK 0.05/kWh. Since the daily variation in the market price of electricity has a standard deviation of DKK 0.05–0.1/kWh, a large consumer with a relatively large consumption in cheap hours may save money paying an hourly price instead of an average price even without changing his consumption. Reducing his consumption in a few very expensive hours will increase the profitability of hourly billing, further.

For a typical household using 4,000 kWh/y the current fee for hourly billing is prohibitive, however. For domestic consumption to react to changes in production from intermittent sources such as wind power, consumers need better incentives to track and react to the price of electricity, or control technologies that will do this automatically.

Another way to create demand flexibility may be to introduce dynamic tariffs and taxes. Unlike hourly market pricing, dynamic taxes are not optimal from a resource economic point of view, as taxes should be lump sum in order not to distort the economy. However, dynamic taxes may be justified in terms of existing market failures: the market price reflects short-term marginal production costs, but does not fully take into account long-term costs such as those relating to peak capacity and grid expansion.

Replacing part of the current high fixed payments, such as those covering transmission and taxes, with a percentage based on the hourly market price will considerably increase the financial incentive for consumers to change their consumption profiles. To allow such a system to create fairly predictable revenues both for the power companies and from taxes, it might be necessary to adjust the percentage each quarter, as Denmark now does with the PSO payment that supports renewable energy. If the percentage is fixed for a year in advance, both tax revenues and consumer bills will fall in wet years (when Scandinavian hydropower is plentiful and power is cheaper) and rise in dry years. This gives unfortunate short-term consumer incentives and may be politically unacceptable.

Figure 38
Average hourly electricity consumption for Denmark in 2009, arranged by month.
Demand peaks at 5 GW on winter afternoons at around 5.00–6.00 pm. Half of this peak is created by domestic users.[119]



The main objective is to reduce peak loads and hence the need for expensive and often fossil-fuelled peak load capacity, as well as facilitating the growth of wind power. This can be done by making smart meters available, by changing regulation and economic incentives and thereby giving households cheap and easy access to the hourly electricity market, or through dynamic tariffs and taxes.

Efficient use of district heating

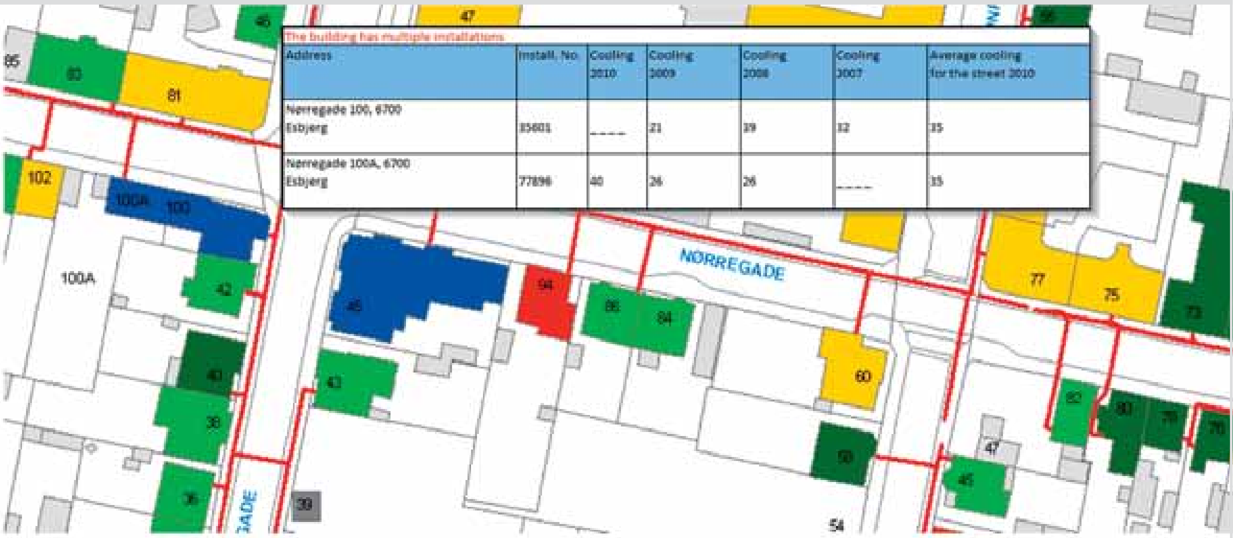
District energy schemes can provide both heating and cooling. Though district cooling is not yet widely applied, in Denmark 60% of households have access to district heating. District energy can use many different energy sources, including surplus heat from power plants, solar energy, biomass and wind. Today 40% of Danish district heating is supplied from sustainable energy and this percentage is expected to increase substantially in the coming years, for instance through the construction of large solar heating and geothermal plants.

The complexity of the Danish energy system is increasing: more wind energy, for example, means fewer operating hours for CHP plants, so less heat is available. As a result, energy production is becoming more diversified in both the electricity and heating sectors. Integration between these two sectors is also increasing through the growth of electric water heaters and heat pumps.

Providers of district heating want the return temperature of the water to be low, since this means a larger amount of heat extracted from the outgoing hot water and hence less water to be pumped around the circuit. Furthermore, low return temperatures increase the efficiency of combined heat and power (CHP) plants supplying the district heating grids. The supply temperature, however, should also be low, since this reduces heat losses (which are currently around 20%) and enables use of lower temperature heat sources. These two requirements imply that the equipment in each building should extract as much heat as possible from the circulating water while operating at the lowest possible temperature.

Figure 39

Visualising the efficiency of individual households in their use of district heating can be a valuable energy-saving tool[120].



Cooling is the difference between the forward temperature and the return at the building installation

Building with multiple installations; The annual cooling less than 20°C; The annual cooling 20 – 30°C; The annual cooling 30 – 40°C; The annual cooling more than 40°C

In Denmark, district heating providers can levy a fine on consumers who return their water at too high a temperature (e.g. due to incorrect use of radiators) or a discount for returning at a lower temperature (the "motivation tariff"). Esbjerg, the fifth-largest city in Denmark, does something more. Instead of just applying a motivation tariff, district heating provider Esbjerg Supply allows customers to view their performance on its website.

In fact, the visualisation tool shows every customer how every other customer is doing in terms of the difference between the supply and return temperatures of their district heating water (Figure 39). Though Esbjerg Supply still uses a motivation tariff, it believes the visualisation tool is more likely to create constructive dialogue with customers. The company says this is borne out in practice, and that visualisation has yielded more efficient consumers who make better use of their heat.

Reducing return temperatures by replacing old heating installations can mean warmer houses and lower bills, as well as benefiting the district heating provider. Esbjerg Supply therefore pays plumbers to offer a free inspection to houses where the temperature difference between the supply and the return water is less than 20°C.

So far Esbjerg Supply has paid for 2,000 inspections. The plumbers have taken the opportunity to tell householders and caretakers how to manage their heating systems better, and this has led to an increase in the difference between the overall supply and return temperatures. The visualisation tool has also prompted many customers to operate their heating better even without an inspection, in many cases contacting Esbjerg Supply for advice.

Like every other Danish district heating company, Esbjerg Supply is a non-profit organisation. Lowering the cost of supplying district heating by improving a relatively small number of domestic installations therefore lowers the cost of heating for everyone.

So far no other district heating company has copied the Esbjerg idea. This may be because of concerns about privacy: not everyone agrees that it is right to make consumer data public in this way.

Another district heating supplier, Viborg District Heatings, has reduced net- losses in the grid by 11% over the last ten years by making use of the motivation tariff. The temperature of Viborg's supply and return has both fallen by 10°C, corresponding to a saving of 8,000 MWh/y.

If all of Denmark's district heating suppliers could cut their distribution losses by 11% this would save around 3 PJ/y nationally. The scale of this saving is certainly an argument for some loss of privacy in return for an increase in the common good, though experience at Viborg shows that big savings can also be made without publishing private data. In general district heating consumers have little attention on their use of heat. The examples in the section show the potential efficiency gains which can be achieved by informing the district heating customers about the efficiency in their use of heat and motivating them economically to change behaviour.

Improving public transport

Public transport is widely thought of as a good thing, but is not always as widely used or as convenient as it might be. New ways to increase opportunities or customer satisfaction are therefore valuable because they can increase the proportion of people who use public transport, and make public transport accessible to people whose infirmity or rural location now obliges them to travel by car.

Technological change has fundamentally influenced the functions and forms of cities and the way people and goods travel in the city. The convergence of computing with information and communication technologies (ICT) has yielded user-friendly interfaces for many types of transaction in education, business and social activities[121]. ICT networks and applications can improve transport and mobility by for example:

- reducing the need to travel; examples of ICT-based alternatives are e-health and e-care, e-learning, e-working, e-culture, e-media, e-economy, e-mobility, e-government and e-democracy;
- significantly improving traffic efficiency and safety through intelligent traffic management; and
- improving links between public transport services.

Table 5
Energy use per passenger kilometre using different modes of transport (2005).[127]

Transport mode	MJ/passenger-km
Private car	1.65–2.45
Private motorcycle	0.92–1.25
Public bus	0.32–0.40
Electric railway and public transport	0.53–0.65

The relationship between telecommunication and transport has long being discussed[122]. For the most part we expect synergy: the more tele-communication that takes place in one form or another, the more all forms of communication and travel are stimulated, though some types of travel are eliminated[121].

A crucial goal of urban sustainability and climate mitigation efforts is to substantially increase the proportion of people who travel by public transport[123]. Real-time information has great promise as a way to do this.

"Smart travel planning" refers to the use of ICT to provide opportunities for innovative traffic management programmes. These can increase the quality, reliability and attractiveness of public transport and overall customer satisfaction – all factors that can increase the number of people using public transport, particularly when fuel prices are rising or there are extra charges aimed at cutting traffic congestion during peak hours.

Information systems relevant to the travelling public are developing at an amazing pace, many actors are taking part, and new opportunities are developing constantly. People are becoming increasingly comfortable accessing services, information and social networks online. There is a role for ICT in automating the supply of information about transport services and so making public transport users better informed and more satisfied.

For example, collecting information from a variety of service providers (traffic conditions, bus schedules, car pools and van pools) and presenting it to the user in one place (telephone system, public kiosk, website) makes travel easier[124]. ICT can also help to improve the services themselves, for instance through mobile ticketing or the rural Danish Flextrip service, where an automated system plans trips using taxis and minibuses based on the trips booked.

A good example of travel planning is the cooperation between the four major public transport companies serving Copenhagen[125]. The companies understand that most customers have to use more than one transport provider to complete their journeys, and that better information is urgently needed to help passengers change between trains, metro and buses. The project has not been easy because on many routes the four companies are competitors, but they are working together because they realise that in the end better information will benefit them as well as their customers.

Another example is the mobile ticketing offered by Danish railway company DSB[126]. The service provides not only tickets but also real-time personalised travel information and the ability to send comments, share, or simply stay connected throughout their train journey.

The partnership of public transport authorities around Copenhagen has also experimented with mobile ticketing. A trial in March 2010 offering discounted 10-trip travel cards by SMS was an immediate success and daily ticket sales increased by 20,000. Another successful example is an iPhone app that reserves seats and buys tickets. Rail company DSB believes that smartphone apps and a segmented approach, for example targeting young people with special deals, will be good for future business.

These examples are just a few of the many available. Improvements and opportunities resulting from the continuing development of smart travel planning can be expected to help resolve transport problems such as road safety, congestion management and, in combination with other policies, CO_2 emissions. Increased use of public transport is important because there is strong evidence that the choice of transport mode determines the amount of energy used for travel (Table 5).

Table 6

Emissions per passenger kilometer for various modes of transport.
Emissions from electric trains are based on emissions from average Danish power production.[128]

	g/passenger-km						**Vehicle Passengers**	
	Particulates	NO_x	SO_2	CO	HC	CO_2	Occupancy	Capacity
Private car (diesel)	0.029	0.445	0.005	0.113	0.022	110.0	1	4
Bus	0.029	1.044	0.004	0.229	0.066	107.9	10	46
Train, electric	0.002	0.044	0.015	0.030	0.003	44.8	168.7	506
Train, diesel	0.002	0.243	0.010	0.028	0.014	42.8	96.0	288
Taxi (3 people)	0.01	0.148	0.002	0.038	0.007	36.7	3	4

Table 6 shows that not just CO_2 (representing energy use) but all forms of emissions could be reduced by increasing the use of public transport modes and maintaining a high level of service, so that the occupancy of buses and taxis increases.

An expansion of smart travel options, in particular those that give urban travellers more choice and better services, or increase vehicle occupancy rates (for example car sharing or flexible taxi services in rural areas), can change people's behaviour in ways that provide substantial gains for the climate, environment and society. Sometimes better information provides the final motivation for people to use public transport.

Further references for this chapter: 129,130.

Conclusions

Getting consumers sufficiently motivated to make future cities sustainable is always going to be challenging. Smart technologies and economic motivation are necessary, but not always sufficient; they may need to be backed up by new regulations and better supply of information. However, our examples drawn from electricity, district heating and transport show that smart technical solutions already exist, are being used in cities today, and can make a real difference to human behaviour.

Synthesis

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Close to 4 billion of the world's current 7 billion people now live in urban areas. This figure is expected to increase to nearly 5 billion by 2030 and to more than 6 billion by 2050. Cities thus will absorb most of the world's population increase over the next four decades, during which world population is expected to surpass 9 billion. Most of the urban increase will take place in developing and less-developed countries. In Africa around 50% of the population is expected to live in urban areas in 2030, while in Asia Pacific the corresponding figure is around 52%.

A world of 29 megacities by 2025

The number of megacities and other very large urban settlements will increase significantly. In 1975 the world had just three megacities – cities with more than 10 million people. Since then another 18 megacities have evolved, and the number is expected to increase to 29 by 2025. Only five of these will be in OECD countries, illustrating the fact that the dominant urban development will be in developing countries.

Urban density and the spatial organisation of cities are important parameters for energy consumption especially for transport but also for residential and commercial buildings. The dynamics of urban expansion show that density of cities generally decrease as income goes up. This is particularly reflected in the growth of sub-urban areas in OECD countries in the last decades. In 2000 the average density for cities in OECD countries was 2 to 3 times lower than that of developing countries, however along with the rapid urban population expansion in most developing regions the density of cities is also declining basically confirming the same trend.

The decreasing density of cities inevitably leads to increased travel both for work, leisure and shopping. The dominant trend is that the expanding high income part of the populations desire more space and seek this in new expanding suburbs leading to increased transport needs. Analysis by the World Bank shows that lower density is not only affecting energy for transport, but it tends also to pave the way for generally more sustainable cities with lower service cost, higher energy efficiency in general etc.

Big cities must be smart cities

Rapid urbanization creates both challenges and opportunities. One consequence of increasing urban energy consumption is increased air pollution, including emissions of greenhouse gases (GHGs): cities already consume between 60% and 80% of the world's energy and account for a roughly equal share of global CO_2 emissions. At a local level, other urban air pollutants can seriously affect the health of city residents.

Another challenge is the fact that more than a billion people live in urban or peri-urban slums, generally under very poor conditions. On a business-as-usual trajectory the number of slum-dwellers will increase by at least another billion by 2050.

For these and other reasons we need a new approach to what cities should do to become more liveable, economically successful, and environmentally responsible. Megacities of the future need to be smart cities: that is, energy-efficient, consumer-focused, and technology-driven.

This mindset will create opportunities to develop smart cities with new and efficient urban infrastructures optimized for economic activity, energy consumption and environmental performance.

However, only new emerging cities have the possibility of being fully designed according to the concept of smart cities, while redesigning existing cities will have to be based on compromises between existing solutions and new smart solutions.

In the literature, the term "smart city" refers to broad qualities of a city rather than to single aspects. Nonetheless, the concept of the smart city is used in a number of different ways, from individual smart infrastructure projects to overall sustainability. In most cases the use of information and communication technologies (ICT) is an integral part of the smart concept, indicating that real-time on-line communication is necessary for the life of the smart city.

In the context of energy a smart city is a sustainable city with a focus on low energy use, renewable energy systems and small carbon footprints.

Smart cities in Europe

The European Commission launched its Smart Cities and Communities initiative with the aim of meeting the EU's 2020 and 2050 energy and carbon reduction targets while sustaining or improving the quality of life of Europe's citizens. To meet this challenge, the Commission identified five key elements of a smart city:
- active buildings;
- decentralized, renewable energy supply technologies;
- smart energy grids;
- low-carbon mobility; and
- urban energy planning.

For the concepts and technologies associated with smart cities to be successfully implemented and operated, these need to be understood and accepted by those who finance, govern, design, install and use them. These socio-economic aspects are of paramount importance in meeting the objectives of the smart city. Getting the right stakeholders involved in the right way and at the right time, and developing the appropriate business models, financial schemes, regulations, and legal frameworks, requires an integrative stakeholder process.

Smart city initiatives in existing cities are embedded in ongoing planning initiatives and models, so the actual choices of technologies and designs will depend very much on what is going on already. This also implies that the processes leading to the planning and implementation of smart cities require cross-sector involvement from professionals, decision-makers, and other stakeholders.

Many elements of the smart city vision have already been implemented in Amsterdam, where energy-related initiatives include:
- electric vehicles;
- solar-lit tram stops and billboards;
- integral refuse compactors;
- ships connected directly to the grid while they are docked;
- smart buildings;
- smart meters;
- energy-saving street lighting; and
- fuel cells providing electricity and heat to apartments.

Several Danish municipalities have become interested in smart city projects. Among them is Copenhagen, which plans to become a sustainable and smart city focusing on energy, climate change, and broader environmental issues. Copenhagen's plans cover four main areas:
- green energy consumption;
- green energy production;
- green mobility; and
- adapting to climate change.

In several respects Copenhagen has already come far in terms of sustainability. For example, almost every household is connected to the district heating network; a large number of wind turbines supply the power system; and 55% of citizens cycle every day. Copenhagen also has a smart grid strategy to manage electricity consumption intelligently. In the new parts of the city now being planned and built there is a strong focus on sustainability in a broad sense; an example is the urban development project in Nordhavn.

The smart city concept can create platforms for the establishment of broad networks and collaboration between the business sector, research, local governments and other partners. With care, the result can be a good basis for knowledge sharing and the development of innovative solutions.

As smart cities require new infrastructure, the timeline for planning and implementing projects is of the utmost importance.

Smart cities worldwide

As every existing city is different in terms of its history, size, climate, and complexity, so its transition towards a smart city has different characteristics.

Curitiba, with a population of around 1.9 million, is the ecological capital of Brazil. Curitiba has concentrated on developing transport systems to allow efficient public transport without hindering private vehicles. Roads have dedicated lanes for bus rapid transit systems. The ticketing system allows passengers to move easily between transport systems, and with as many as 2 million passengers per day prices have been kept affordable even for low-income households.

New cities can take a broader approach to the integration of energy, water, waste, and transport, as it is seen in the greenfield development of Masdar City in Abu Dhabi.

Characteristics of Masdar's energy systems include:
- energy consumption minimized through stringent building efficiency standards, low-energy lighting, smart metering, and a smart energy control system;
- the city's orientation from north-east to south-west lessens the effect of the hot daytime wind and takes advantage of cool night breezes;
- on-site renewable energy production from photovoltaics (PV) and wind farms;
- sidewalks and paths constructed to promote walking; and
- an integrated public transport system based on light rail, metro, and electric buses.

Smart buildings

Buildings are responsible for as much as 38% of the energy consumption in the EU and 40% in the USA. This has led to an increasing interest in smart buildings whose systems show a high degree of interoperation aided by ICT. Large numbers of sensors monitor almost everything from temperature and humidity to precipitation, light levels, room occupancy and the movement of people. Actuators and smart materials then react to these measurements, ensuring that energy and other resources are used only when needed.

Creating smart buildings requires concerted action from a number of actors: legislators, building professionals, investors, and homeowners. Given the long lifetime of buildings, the bulk of the potential for smart buildings lies in renovating the existing building stock.

Smart energy networks

Smart energy networks will allow greater energy efficiency and flexibility in energy use in smart cities. This involves a combination of ICT and energy networks.

Smart energy networks also allow room for the development of decentralized or localized energy production and consumption. This has multiple advantages. Primarily, energy efficiency improves because long distribution networks are no longer required. Instead, energy is produced close to the points of consumption. This requires the use of new, decentralized methods of production and efficient control mechanisms to manage energy in small local networks.

Supply needs to match demand in power systems, so some form of demand response is needed to integrate distributed generation and especially to ensure the smooth running of networks supplied largely from fluctuating renewable sources. Ways to do this in smart cities include sophisticated control systems, localized energy storage, and real-time updates of power usage and pricing.

The first step towards better load management is better and smarter metering. Real-time communication of power prices gives consumers an incentive to reduce energy use during peak periods, either automatically or via conscious decisions about when to switch equipment on and off as prices change.

At the moment a large proportion of the world's primary energy supply is wasted in the form of heat loss from power plants. Greater use of district heating would therefore lead to a marked improvement in energy efficiency. District cooling can be supplied in a similar way, using either local sources of cold – such as seawater or groundwater – or left-over heat from district heating to provide cooling with greater energy efficiency than is possible with electrically powered air conditioning.

Finally, the natural gas network can also be integrated with the power and heating networks. Such an arrangement allows natural gas to fuel micro-CHP plants (see below) that help the power system to meet demand peaks.

Smart transport

Urbanization has led to significant transport challenges of which the two most important are:
- increased traffic congestion in many places;
- transport accounts for a major and rising share of total GHG emissions – up to 50% by 2050.

The solutions to both these challenges must go hand in hand, as maintaining high mobility is considered a prerequisite of economic growth.

The key issue for transport is a technological shift to new energy forms with radically lower lifecycle GHG emissions. At present the main tracks for this transformation appear to be:
- biofuels in conventional internal combustion engines;
- electric propulsion;
- extending the driving range of existing electric cars;
- hydrogen, which offers a driving range much closer to that of petrol and diesel.

In urban areas non-fuel-consuming transport should be encouraged. Walking and cycling should be supported by attractive networks of lanes allowing safe and rapid movement.

The future energy supply is likely to come primarily from solar and wind power in the form of electricity. Public transport in cities should therefore be basically electric. However, supplying buses and trains directly from the grid creates extra demand during rush hours, when energy demand is already high. At least part of the power needed for public transport should therefore be detached from the grid through the use of energy storage technology in the form of batteries or fuel cells.

Although a well-working public transport system can cover a large fraction of a city's transport needs, individual transport will persist, especially for moving people and goods into and out of cities. Electric vehicles – whether powered by batteries or fuel cells – should be able to provide individual as well as public transport, but need further R&D attention. One aspect which appears to be often overlooked is that the costs of the infrastructure needed to charge battery vehicles vary significantly between different types of housing.

The only real competitor to electricity – used either directly or indirectly – for future urban transport is fuel produced from biomass. In theory, marine biomass in the form of algae grown within the city limits has tremendous potential as a fuel (see below).

Energy technologies for smart cities

Energy supply in smart cities should be highly distributed. Cities should be largely self-sufficient in energy so as to minimize the need to bring electricity, district heating and cooling, natural gas and liquid fuels from distant sources. As well as requiring huge investments in grid capacity, such long-distance transport involves significant energy losses.

Cities can meet their own energy needs through a range of renewable energy technologies, suitably modified for the urban environment. The use of intermittent renewable energy, electric vehicles and other innovative energy technologies will require load management mechanisms (see above) to ensure that supply always meets demand.

Wind

In recent years the idea of erecting wind turbines in the built environment has created a fast-growing new market for small wind turbines (SWTs). In Denmark, new regulations have recently made it financially attractive for citizens to erect their own private wind turbines.

The supply side is setting the agenda: the number of certified or notified SWTs has doubled in one year, with another doubling forecast on the basis of the number of prototypes currently going through the certification process.

Depending on the location, urban wind potential can be used in several different ways. In Tokyo, for example, wind close to buildings and at low heights is harvested by so-called drag-driven horizontal axis wind turbines (HAWTs). Where wind speeds are higher, larger lift-driven vertical axis wind turbines (VAWTs) are typically more appropriate.

Another way of using wind is to ventilate buildings. Clever design methods allow architects to make direct use of pressure differences created by wind or temperature gradients, without involving electric energy at all.

Micro-CHP

Combined heat and power (CHP) is the simultaneous generation of thermal and electrical energy in a single unit. In cities, small-scale CHP units may be attractive to add flexibility to energy systems.

The EU defines micro-CHP as units with an electrical capacity below 50 kWe. Although 1 kWe is sufficient to cover the average power consumption of a typical household, peak demand may be several times larger. The household will therefore still need to be grid-connected, and this has the added advantage that surplus power may be exported to the grid.

When heating is not required, the heat from micro-CHP units may be used to drive an absorption cooling cycle for refrigeration or air conditioning. Widespread use of micro-CHP will increase the flexibility of the total energy system by adding a large number of individual generating units with the ability to up- and down-regulate rapidly.

From the systems viewpoint, micro-CHP can increase the efficiency of the energy system because local generation of power and heat avoids transmission losses. From an end-user viewpoint, micro-CHP currently still costs significantly more to install than a traditional boiler. This makes market entry sensitive to factors such as favourable legislation and tariffs.

Several different micro-CHP systems are on the market or close to the market. These include systems based on fuel cells, which convert the chemical energy of a fuel directly into electricity, generating heat in the process. Fuel cells, in particular the solid oxide variety (SOFCs), can be designed for reversible operation, according to demand either generating power or electrolyzing water to produce hydrogen. This can bring added flexibility to the energy system by allowing surplus wind or solar power to be stored as hydrogen in the natural gas grid. Such systems, however, have only been tested at the lab scale so far.

Ordinary internal combustion engines (ICEs) are a well-proven technology. The main advantages of micro-CHP based on ICEs are their simple and proven technology, fuel flexibility, and relatively low cost.

Another technology is the Stirling engine, distinguished by the fact that combustion takes place outside the cylinder, as in an ordinary boiler. Several micro-CHP products based on Stirling engines have been released to the market, and the technology is approaching maturity.

The outlook for micro-CHP thus looks promising, with different technologies at or close to commercialization.

Bioenergy

The organic components of municipal solid waste (MSW) and other organic waste streams are sources of biomass that can be converted to energy within smart cities.

Electricity and heat can be produced by incineration of MSW. It is estimated that about 130 million tonnes of MSW are combusted annually in over 600 waste-to-energy (WTE) facilities worldwide, producing electricity and steam for district heating.

Gasification of MSW produces syngas, which has an energy value approximately half that of natural gas. Gasification represents a future alternative to incineration for the thermal treatment of MSW.

In US the first facility to produce both ethanol and electricity from waste will begin production in 2012.

An innovative way to produce biomass within city limits could be by converting flat rooftops into facilities to produce blue-green algae. Given the right temperatures and nutrients, algae can grow far more rapidly than other forms of biomass, and can be continually cropped to produce biofuels or to fuel micro-CHP plants. Roofs could be designed to harvest water, collect solar energy and grow algal biomass.

Micro-algae grown in sewage treatment plants can also be used to produce biodiesel. This is a valuable symbiosis because the micro-algae help the water purification process by taking nutrients from the wastewater.

Urban agriculture refers to the production of crops and livestock in cities, towns and surrounding areas. Urban agriculture seems particularly important in low-income countries, but even in more developed economies a significant fraction of urban households are involved in farming.

Urban agriculture can be made smart through the development of new low-energy concepts such as "vertical farming", soilless indoor systems, and the use of waste streams from the city. These concepts could make farming smart and distributed, in the same way as energy. Urban agriculture in smart cities would minimize energy use for transport and provide fresher food for citizens.

Heat pumps

A heat pump supplies heat at the required temperature by utilizing two energy inputs: a low-temperature heat source and a source of driving energy, which may be either mechanical power or high-temperature heat. It is thus a way to make use of low-temperature heat from industrial processes, for instance, or solar heat stored in the ground.

Heat pumps are basically a mature technology and are already used to heat residential buildings, but there are significant opportunities to improve their performance.

Smart cities may benefit from the integration of heat pumps due to the dense population which may reveal significant potential for optimization of heat supply such that exergy (the energy that is available to be used) losses may be minimized, and thus best possible utilization of the energy sources may be reached.

Solar

Both solar thermal heating (and cooling) and photovoltaics (PV) are modular technologies that can be built into residential, public and commercial buildings, as well as other constructions such as highway noise barriers. Centralized solar power or heating stations near cities may connect to the grid or the district heating system.

For solar to be truly competitive with traditional power sources, the cost and efficiency of turning sunlight into heat, cooling, and electricity need to improve further. Few – if any – other renewable energy technologies show such a portfolio of available technical options at different levels of maturity as solar PV.

Building integrated PV (BIPV) replaces conventional building materials in parts of the building envelope. BIPV includes PV incorporated into the construction of new buildings and old buildings retrofitted with solar cell modules. Rooftop-mounted panels are generally not considered BIPV unless they also constitute an architectural element.

Smart consumer behaviour

Many of the smart technologies needed for better energy management already exist and are being implemented today. In contrast, it will be a challenge to motivate consumers in smart cities to achieve sustainable development through smarter use of energy.

The overall aims are to reduce peak loads and facilitate the use of more renewable energy in the electricity system. Consumers can be motivated to use energy wisely through economics, information, education, regulation, reorganization, or through improved services or comfort.

Optimal operation of electric appliances means reducing consumption, and equally importantly using electricity when excess capacity is available and the market price is low. For households, however, incentives to change consumption profiles or to react to hourly market prices are currently very limited.

For electricity consumption to become flexible enough to react to changes in production from volatile sources such as wind power, consumers therefore need to be able to react to short-term changes in the price of electricity. Once the price information is available, consumers can respond by switching off appliances when the price is high, or by investing in control technologies that react automatically to price changes.

To increase incentives for demand flexibility, in addition to hourly prices, dynamic tariffs may also be considered.

Providers of district heating want the temperature of the water returning to the district heating plant to be as low as possible, since this minimizes the amount of water to be pumped around the circuit. In Denmark, providers of district heating can give consumers a fine in the form of an extra bill if they do not cool the water sufficiently; this is called the motivation tariff.

Appendix: Selected smart city initiatives that include energy goals

Table 7

Selected smart city initiatives that include energy goals.

Region	Country	City	Energy related initiatives	Reference
Asia	China	Dezhou	Solar water heaters Solar park	Risø Energy Report 10, p. 43
Asia	China	Langfang Eco-Smart City	A City Center Transportation Hub, a Northern Gateway Cultural Corridor, and an extensive wetland and aquifer system. Located in the heart of the city and bridging the high speed rail-line, the transportation hub weaves together transit systems, living infrastructure, and compact development to create a pedestrian-scaled, multi-tiered canopy for working and living	http://www.archdaily.com/107090/langfang-eco-smart-city-woods-bagot-hok/
Asia	China	Shanghai	Renewable energy Increased gas supply Improved energy efficiency in industry, transportation, buildings and new source of energy Underground lines for public transportation Green/electric cars	Energy and urban innovation, WEC, 2010, p. 112
Asia	India	Delhi	Public transport shifted to compressed natural gas Energy efficiency in new and existing buildings City metro rail Shift from coal to gas in power plants "Solar mission"	Energy and urban innovation, WEC, 2010, p. 97
Asia	India	Gift	Greenfield city project to be a test-bed to drive reforms and innovation in various fields including delivery systems, local government, physical planning, infrastructure development, environmental protection. Focus on low energy consumption; careful stewardship; reduction in wastes and protection of diverse and important natural species and systems	http://giftgujarat.in/index.aspx
Asia	India	Nagpur, Maharashtra	Renewable Energy and Energy Efficiency policy. Objectives include renewable energy; renewable energy sources for all city applications like traffic signals; waste-to-energy projects; First solar city in India	Cities, towns & renewable energy, IEA, 2009, p. 123 http://www.iclei.org/uploads/media/LR_Nagpur_policy_bali.pdf
Australia and Oceania	Australia	Adelaide, Alice Springs, Blacktown, Central Victoria, Moreland, Perth and Townsville	Adelaide's Carbon Neutral Action Plan 2008-2012 sets the goals to reach zero net greenhouse gas emissions in buildings by 2012 and in transport by 2020. The rest are "Solar cities"	Cities, towns & renewable energy, IEA, 2009, p. 126 http://www.adelaidesolarcity.com.au/ Risø Energy Report 10, p. 43
Europe	Austria	Güssing	Biomass gasification CHP plant Solar PV plant District heating Bio-SNG and biodiesel for transport	Cities, towns & renewable energy, IEA, 2009, p. 165 http://www.ecreag.com/dok/modellregion_guessing_deutsch.pdf
Europe	Austria	Smart City Vienna	Meeting the European Commission's 2020 and 2050 targets for energy efficiency, renewable energy production and carbon reduction	Risø Energy Report 10, p. 16
Europe	Denmark	Ærø	Large solar heating plant	Risø Energy Report 10, p. 41
Europe	Denmark	Kalundborg	Industrial Symbiosis, in which participating companies use each other's waste products and by-products Moving from 15% renewables to 85% renewables	Risø Energy Report 10, p. 20
Europe	Denmark	Vejle	Renewable resources	Risø Energy Report 10, p. 21

Table 7 (continued)

Selected smart city initiatives that include energy goals.

Region	Country	City	Energy related initiatives	Reference
Europe	France	Paris agglomeration	Increased share of renewables in district heating Reduced energy consumption in new buildings and retrofitting	Energy and urban innovation, WEC, 2010, p. 101
Europe	Germany	Freiburg	Solar PV Wind turbine farm Biomass CHP plant Landfill gas for CHP Small hydro-power plants Solar thermal City trams on 80 % hydro-power	Cities, towns & renewable energy, IEA, 2009, p. 136 http://www.fwtm.freiburg.de/servlet/PB/menu/1182949_l1/index.html http://www.c40cities.org/bestpractices/energy/freiburg_ecocity.jsp
Europe	Germany	Innovation-City Bottrop	Transformation to a low-carbon city Energy-efficient redevelopment of existing buildings and infrastructure	Risø Energy Report 10, p. 15
Europe	Netherlands	Amsterdam	Amsterdam Smart City is an initiative of the Amsterdam Innovation Motor (AIM) and the grid operator Liander, in collaboration with the city government. Includes initiatives such as electric vehicles; solar-powered lighting for tram stops and billboards; integral compactors; "Ship to grid"; smart building; Smart meters; Smart plugs and energy-saving street lighting	http://www.amsterdamsmartcity.nl/#/en Risø Energy Report 10, p. 18
Middle East and North Africa	United Arab Emirates	Masdar City, Abu Dhabi	A green field project to create a smart city supplied entirely by renewable resources, including among others solar PV and CSP; geothermal heat pumps; grid management; geothermal cooling; pedestrian network and light rail	Cities, towns & renewable energy, IEA, 2009 http://www.masdar.ae/en/home/index.aspx Risø Energy Report 10, p. 15
North America	Canada	Toronto	GHG emission reductions by coal phase out, renewables and other electricity policies like electrification of the commuter rail transport system	Energy and urban innovation, WEC, 2010, p. 119
North America	Mexico	Mexico City	Biogas capturing program (CDM) Increased energy efficiency Increased public transportation	Energy and urban innovation, WEC, 2010, p. 105
South America	Brazil	Curitiba	Curitiba has come a long way in terms of addressing some of the challenges with urban expansion. Transport system allows both private vehicles and an efficient public transport system	Risø Energy Report 10, p. 12
Sub-Saharan Africa	South Africa	Cape Town	First city in Africa to implement Integrated Metropolitan Environmental Policy (IMEP). Include among others pumped storage plant; wind farm; solar thermal as well as bicycle and pedestrian transport	Cities, towns & renewable energy, IEA, 2009, p. 120 Energy and urban innovation, WEC, 2010, p. 94 http://www.capetown-greenmap.co.za/

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Fossil fuels provide about 80% of global energy demand, and this will continue to be the situation for decades to come. In the European Community we are facing two major energy challenges. The first is sustainability, and the second is security of supply, since Europe is becoming more dependent on imported fuels. These challenges are the starting point for the present Risø Energy Report 6.

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The report presents state-of-the-art and development perspectives for energy supply technologies, new energy systems, end-use energy efficiency improvements and new policy measures. It also includes estimates of the CO_2 reduction potentials for different technologies. The technologies are characterized with regard to their ability to contribute either to ensuring a peak in CO_2 emissions within 10 – 15 years, or to long-term CO_2 reductions. The report outlines the current and likely future composition of energy systems in Denmark, and examines three groups of countries: i) Europe and the other OECD member nations; ii) large and rapidly growing developing economies, notably India and China; iii) typical least developed countries, such as many African nations. The report emphasises how future energy developments and systems might be composed in these three country groupings, and to what extent the different technologies might contribute.

Edited by Hans Larsen and Leif Sønderberg Petersen

Risø DTU, October 2008, 86 p., ISBN 978-87-550-3690-1, Risø-R-1651(EN)

Risø Energy Report 8

The intelligent energy system infrastructure for the future

The report take its point of reference in the need for the development of a highly flexible and intelligent energy system infrastructure which facilitates substantial higher amounts of renewable energy than today's energy systems. This intelligent and flexible infrastructure is a prerequisite in achieving the goals set up by IPCC in 2007 on CO_2 reductions as well as ensuring the future security of energy supply in all regions of the world.

The report presents a generic approach for future infrastructure issues on local, regional and global scale with focus on the energy system.

The report is based on chapters and updates from Risø Energy Report 1 – 7, as well as input from contributors to the DTU Climate Change Technology workshops and available international literature and reports.

Edited by Hans Larsen and Leif Sønderberg Petersen

Risø DTU, September 2009, ISBN 978-87-550-3755-7, 72 p.

Risø-R-1695(EN)

Risø Energy Report 9

This Risø Energy Report, the ninth in a series that began in 2002, analyses the long-term outlook for energy technologies in 2050 in a perspective where the dominating role of fossil fuels has been taken over by non-fossil fuels, and CO_2 emissions have been reduced to a minimum.

Against this background, the report addresses issues like:

- How much will today's non-fossil energy technologies have evolved up to 2050?
- Which non-fossil energy technologies can we bring into play in 2050, including emerging technologies?
- What are the implications for the energy system?

Further, Volume 9 analyses other central issues for the future energy supply:

- The role of non-fossil energy technologies in relation to security of supply and sustainability
- System aspects in 2050
- Examples of global and Danish energy scenarios in 2050

The report is based on the latest research results from Risø DTU, together with available international literature and reports.

Edited by Hans Larsen and Leif Sønderberg Petersen

Risø-R-1729(EN).

Risø DTU, November 2010, ISBN 978-87-550-3812-7, 90 p

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